

WITH LIQUID-CRYSTAL LIGHT VALVES AND SCANNING READING BEAM

1. FIELD OF THE INVENTION

This invention relates generally to devices for projecting pictures onto large viewing screens; and more particularly to such devices that project laser beams via reflective liquid-crystal light valves to form such pictures. The invention has its most important applications in such projection of moving pictures.

2. RELATED ART

a) Known potential of lasers — Since the advent of the laser, people have been trying to find new ways to use lasers in projecting pictures of one kind or another, for large audiences. This is both natural and reasonable, since lasers offer several important characteristics that are relevant in large-image projection.

1 As will be seen from the following recap of these charac-
2 teristics, one would expect these characteristics to be re-
3 sponsible for a predominance of laser projection systems in
4 large-screen displays for both video home use and theater-
5 scale displays. Indeed, several powerful large international
6 companies have attempted — at monumental cost — to develop
7 such equipment for market.

8 Therefore, while reading the following discussion of
9 laser advantages for large-screen projection sources, please
10 bear in mind this overriding question — why are large-screen
11 laser projectors not common in the marketplace?

12 (i) energy efficiency — All other things being
13 equal, the amount of light needed to show any kind of picture
14 on a projection medium (viewing surface) is proportional to
15 the area to be covered by the picture. Optical energy is
16 therefore of utmost importance in a large-format projection
17 system, and it is necessary to pay for visible optical energy
18 with electrical energy.

19 In such transactions it is well understood that some con-
20 version inefficiency is unavoidably involved as a sort of tar-
21 iff — in other words, that a sizable fraction of the electri-
22 cal energy used will go into invisible forms of energy such as
23 heat, or near-infrared and ultraviolet radiation. Normally
24 there is relatively little objection to this price in itself,

1 but the question does arise of just how sizable a fraction one
2 can afford.

3 With nonlaser light sources, this concern is compounded
4 when taking into account the additional surcharge for optical
5 energy that is visible but goes off in directions other than
6 into the collecting optics of a projector. Most nonlaser
7 sources (incandescent hot-filament or arc lamps) radiate
8 approximately equally in all directions. The amount of
9 visible light that can be directly collected from such a
10 source into an optical system is typically less than a tenth
11 of the visible light produced.

12 It can be dismaying to pay for many times the amount of
13 electrical energy used — even that which is directly used to
14 make visible light, setting aside consideration of the conver-
15 sion efficiency discussed above. Therefore it is common to
16 provide reflectors behind the source, or more generally speak-
17 ing to try to surround the source with reflectors to help
18 capture a greater geometrical fraction of the visible energy.
19 Such efforts, however, complicate and compound the management
20 of heat thrown off due to those same conversion inefficiencies
21 considered above.

22 A laser, though of course itself a costly article, great-
23 ly improves all these energy economics. Since its optical

1 emissions are directional, essentially all the emitted light
2 can be very easily captured for use.

3 Furthermore, to a significant extent the spectral compo-
4 nents can be controlled so that minimal energy is wasted in
5 infrared or ultraviolet radiation. A laser is therefore far
6 more energy efficient than other sources — with respect to
7 both raw conversion efficiency of electricity into visible
8 light and geometrical capture of that visible light.

9 Lasers and their power supplies do give off heat, and
10 this must be managed. In comparison with a typical arc lamp
11 or like device, a laser is vastly more favorable with respect
12 to the amount of heat, the temperature involved, and the
13 difficulty of collection.

14 (ii) brightness — With most types of light sour-
15 ces, increasing the amount of light available calls for fabri-
16 cation of a source that is scaled up in all three dimensions,
17 more or less equally, and therefore greatly complicates the
18 process of collecting the light and drawing off heat.

19 To make a brighter laser, it is necessary in essence to
20 make a laser which is just like one that has various desirable
21 known properties, except with a bigger tube. Over a small
22 range of brightness increases, furthermore, what is needed is
23 only a longer tube. Heat management with a longer tube re-
24 duces to using the same hardware, but more of it, as with a

1 shorter tube. Even if brightness requirements do call for
2 increased diameter too, the elongated character of most laser
3 structures tends to distribute and thus mitigate the problems
4 of power and heat management.

5 With a bigger laser, all the greater amount of optical
6 flux can be made to go in essentially the same direction and
7 into essentially the same projection system as the correspond-
8 ing smaller laser. These oversimplifications of course slight
9 some practical considerations such as design of power-sup-
10 plies, cooling, and lasing modes, but summarize an important
11 way — for purposes of image formation — in which lasers
12 differ from other light sources.

13 (iii) contrast — Several properties of lasers tend
14 to enhance contrast in a projected image. The simplest of
15 these is once again inherent directionality, which facilitates
16 both collection of input illumination and handling of an im-
17 age, with minimum crosstalk between different portions of the
18 beam or the image.

19 Contrast is enhanced by avoiding such crosstalk — or in
20 other words preventing the spill of a cast over an entire
21 image frame, from bright image areas. Such undesired spill
22 corrupts areas that should be dark. Further enhancement of
23 just the same sort arises from the inherent collimation of a
24 laser beam.

1 Equally or more important, when most modern image-modula-
2 tion devices are taken into account, is the inherent monochro-
3 maticity of a laser beam. Other sources emit light over the
4 entire visible spectrum, requiring subdivision into spectral
5 segments, and physical separation into distinct beams that can
6 be separately modulated and then recombined to give full-color
7 images.

8 In either type of system, laser or nonlaser, the final
9 optical stage — i. e., the projection lens — is preferably
10 broadband since it preferably carries all the colors in a
11 common beam; for this purpose a high-quality achromat is
12 desired. The benefits under discussion apply to all earlier
13 optical stages, where the functions being performed are much
14 fussier and complicated than the final projection stage.

15 With such other sources, each distinct beam carrying a
16 separated spectral segment is already broadband, either
17 complicating or degrading the effectiveness of all optical
18 effects or manipulations. These include everything from
19 perturbation of simple focusing (chromatic aberration) to the
20 operation of sophisticated image-modulating devices (see
21 below).

22 Since operation of lenses, polarizers, prisms, dichroics
23 and image modulators are all wavelength-dependent, the opera-
24 tion of virtually all optical components in a projection sys-

1 tem using such other sources tends to scatter light away from
2 the precise bright-region positions where it should be. The
3 result is to create a kind of halo about such positions — or,
4 again, depending on the brightness contours of a particular
5 image, even to produce a filmy bright cast over much of a
6 scene that should be darker.

7 Also of great importance is the inherent polarization of
8 a laser beam. Many large-screen projectors of the present day
9 employ an image-writing stage that controls a high-intensity
10 light beam by spatial modulation of the beam.

11 As discussed more fully in later sections of this docu-
12 ment, almost all such modulators rely upon formation of a
13 latent image in polarization state (or as it is sometimes
14 called, a "phase object"). This image is later developed by
15 passage through some form of polarization analyzer.

16 Other projectors intensity-modulate a scanning spot of
17 a high-intensity beam; here too, the phenomenon most commonly
18 exploited to accomplish modulation is the polarization of the
19 beam. For all such applications a laser is ideally suited,
20 first of all because no light need be discarded (or recaptured
21 through a complicated optical train) merely because its pola-
22 rization state does not match what can be used by a modulator.

23 More significant to contrast enhancement is the relative
24 sharpness (i. e., narrowness of angular range) of laser pola-

1 rization, in comparison with polarization obtained through a
2 common polarizer. Because of this, in areas of a latent image
3 that should be bright (calling for passage of a beam through
4 the downstream polarizer), the polarization state provided
5 when using a laser source is defined more sharply; the same is
6 true for areas that should be bright and call for extinction.
7 The latent image therefore is potentially brighter where it
8 should be bright, and darker where it should be dark — or, in
9 other words, has better contrast.

10 It is true that the latent image yet remains to be devel-
11 oped through a polarizer, leading to some imprecision in iso-
12 lating for projection the polarization state that is nominally
13 correct. Nevertheless — even based upon the sharper polari-
14 zation definition in the latent image alone — both the beam
15 passage in bright areas and the beam extinction in dark areas
16 are better.

17 (iv) sharpness — Another benefit due to the inher-
18 ent collimation of a laser beam is that it produces sharper
19 images. This is partly associated with contrast enhancement,
20 due to the wavelength- and polarization-dependent effects
21 discussed above. In a scanning-spot projection system (wheth-
22 er amplitude-modulated or not), laser-formed images are shar-
23 per also in part because of the capability of a highly col-
24 limated beam to be focused to a fine spot.

1 In image-modulation systems, laser beams are able to
2 traverse great distances without degradation of spatial mod-
3 ulation. In other words, a spatially modulated beam can carry
4 an image over a long distance without becoming blurry. For a
5 laser system, this performance characteristic may be more
6 associated with favorable divergence properties than with
7 collimation.

8 In any event, except for contrast effects already dis-
9 cussed, the capability of a good arc-lamp-based projector to
10 produce a sharp image at a distance may be about as good as a
11 laser-based system heretofore — provided that the image is
12 projected onto a screen or other viewing surface that is:

13
14 (1) flat or very gently curved,

15
16 (2) essentially at right angles to the beam, and

17
18 (3) not moved toward or away from the projector after
19 the projector is set to produce a sharp image.

20
21 In other words the prior-art laser projector may have little
22 advantage in sharpness as such if the projection medium is all
23 at the same distance from the projector, and there is an

1 opportunity to adjust the projector for the actual projection
2 distance.

3 Cases in which these conditions fail are discussed in the
4 following paragraph. In both types of systems, laser and non-
5 laser, the ability to maintain image sharpness as such over
6 long distances depends to a major extent on the quality and
7 size of the final projection lens.

8 (v) infinite depth of sharpness — Laser systems
9 have a unique and major advantage over white-light systems, in
10 projection onto projection media that are at varying distances
11 from the projector. Such media also can be positioned or ori-
12 ented so that they are not all at a common, preset projection
13 distance.

14 These media can include, for example, surfaces that are
15 strongly angled to the projection beam. In the vector-graph-
16 ics part of the laser-projector field, this is a well-known
17 characteristic — which I have sometimes termed "infinite
18 focus". It is also possible with other types of laser-trans-
19 mitted images, including both vector- and raster-scanned spots
20 as well as images projected with spatial modulators. My phra-
21 seology is mentioned for instance in U. S. Patent 5,317,348 to
22 Randall J. Knize, Ph. D.

23 It has been suggested to me that the term "infinite fo-
24 cus" is a misnomer, in that "focus" refers to formation of an

1 image at a preset "focal plane" (sometimes in the retina) by
2 convergent light rays from various parts of a lens system.
3 Such convergence requires adjustment of the optical system for
4 a specific projection distance — a process with which of
5 course nearly everyone is familiar. My phrase "infinite fo-
6 cus" derives from the concept of "depth of focus", combined
7 with the idea that laser-transmitted images seem to have in-
8 finite depth of focus.

9 As I now understand, however, laser beams when used to
10 project images in such a way as to obtain this effect are not
11 focused at all. The image is not formed by convergence of
12 rays from different parts of a lens, either at a preset "focal
13 plane" or otherwise.

14 Rather an image can be impressed upon a laser beam by so-
15 called "spatial modulation" of the beam. This means that each
16 pencil of rays from the laser carries a specific, fixed part
17 (e. g. pixel) of the image. Laser beams are initially colli-
18 mated so that the ray pencils are all parallel, never crossing
19 one another or converging.

20 It is possible to force a laser beam to converge to a
21 rather fine point (of course only an approximation of a point)
22 by interposition of a lens that does focus all the rays. For
23 present purposes it would not make sense to do this, since
24 there would be no image — only a single bright spot — and

1 indeed this is never done in a system that displays the "infi-
2 nite" effect.

3 Instead the spatially modulated beam is simply directed
4 to a viewing medium, where the ray pencils are stopped and so
5 make the impressed image visible to viewers. In practice such
6 a beam can be expanded, to form a large image on a large view-
7 ing medium, and for this purpose a substantially conventional
8 lens may be employed — and within the constraints of pixel or
9 raster-line visibility the image will be sharp but never
10 "focused".

11 The other half of the phrase "infinite focus" is also
12 somewhat inaccurate since there are some limits to the depth,
13 along the projection direction, at which images appear sharp.
14 These limits are imposed by beam divergence and other dif-
15 fraction effects.

16 For reasons that will appear after I have introduced my
17 invention, however, these effects should never come into play
18 in a laser-based system properly designed and assembled for
19 image projection. Therefore in other parts of this document I
20 have replaced my earlier terminology with the phrase "infinite
21 depth of sharpness" or simply infinite sharpness.

22 It has been recognized that this deep-sharpness effect is
23 of potentially great value for special effects. Some of this
24 value has been actually achieved in some vector systems, as

1 will be explained below, but the much greater potential for
2 raster images has not been realized in practice heretofore.

3
4 The importance of the previously posed question as to the
5 nonappearance of laser projectors in the marketplace should
6 now be apparent. Some reasons for that peculiarity will
7 appear from the following sections of this document.

8
9 b) Vector-scanning laser systems — Generally speaking
10 this term refers to free-form movement of laser beams from any
11 point on a projection medium to any other point, and following
12 any specified trajectory (e. g. curved) rather than a preset
13 framewise pattern as discussed in the next section.

14 (i) light-show style — Historically these were the
15 first displays for large audiences, and are straightforward to
16 produce since equipment was minimal and artistic opportunities
17 maximal. In most cases the beams are neither amplitude modu-
18 lated nor focused (a small-diameter laser tube yielded a small
19 spot for entertainment purposes), and a relatively slow sweep
20 is usually employed so that audiences can perceive the spot
21 motion itself as well as the trajectory. Since the color
22 effects of the independent laser beams are an important part
23 of the show, there is no point in forming or sweeping a
24 combined beam.

1 I mention these early systems primarily because — as
2 long as the beams are not focused — a primitive sort of
3 equivalent of infinite sharpness is enjoyed for each beam
4 independently. That is to say, beams can be projected onto
5 surfaces at considerably varying distances from the lasers
6 without changing spot size.

7 The beneficial uses of this phenomenon are entirely fa-
8 miliar to designers and operators of these shows as a sort of
9 special-effects trick that can be used to enhance light-show
10 imagery. The desirability of extending this phenomenon to
11 infinite sharpness as related to projection of whole picture
12 images is accordingly also believed to be known in this field.

13 It will be understood, however, that in the light-show
14 context spot size does change, to the extent that the beams
15 are spread out on a viewing surface that is angled to the
16 projection beam. (Depending on audience position — i. e.,
17 whether the audience is looking essentially along the projec-
18 tion direction or along a normal to the surface, or from some
19 other direction — the stretching may not be visible in its
20 entirety, or at all.)

21 It is very important to recognize this sort of spreading
22 on an angled viewing surface, and to distinguish it from fai-
23 lure of the beams to be sharp. An analogous spreading/sharp-

1 ness distinction arises later in discussing whole-picture-
2 image projection.

3 (ii) graphics — As in the now-familiar vector
4 graphics of computer programs such as CAD/CAM, Corel® Draw,
5 Visio® and so forth, the use of vector graphics in a laser-
6 based projection system is well understood and highly versa-
7 tile. It may be used to provide economically and quickly a
8 simple, static production nameplate, or a more elaborate mov-
9 ing display for similar purposes, or of course cartoons for
10 entertainment etc.

11 In this case the beams may be amplitude modulated for
12 more complex effects, and the beams may be combined into a
13 composite beam that is swept as a unit — in which case the
14 entire resulting image may enjoy infinite sharpness provided
15 that the beams are simply projected and not focused. As will
16 be seen, vector-graphics projection is of only secondary in-
17 terest for present purposes.

18
19 c) Raster-scanning systems — The topic now turns to re-
20 production of whole picture images that are generalized, in
21 the sense that the projection system is a neutral vehicle for
22 display of any raster-based image. The projection-system
23 raster can be set to match traditional or conventional broad-
24 cast television, whether U. S. interlaced or otherwise, or to

1 match a high-definition television format — or to match a
2 conventional computer-monitor format, or any other well-de-
3 fined raster specification.

4 (i) amplitude-modulated spot, with separately swept
5 beams — In essence such a system would be a direct laser-
6 projector analog of a conventional television set, requiring
7 amplitude modulation at video speeds, and for each color in-
8 dependent two-dimensional sweep. Such devices may never have
9 been put into practice, but they are well represented in U. S.
10 Patent 3,524,011 of Korpel (1968), assigned to Zenith Radio
11 Corporation. (Korpel's independently swept beams optionally
12 share a common projection lens.)

13 Such a system cannot provide accurate infinite sharpness
14 of a full-color image, as introduced above, since Korpel's
15 separately swept individual-color beams emanate from spaced-
16 apart points (possibly even spaced-apart projection lenses)
17 and can therefore accurately converge to form a registered
18 image only at a preselected plane. If, however, the projec-
19 tion distance (or audience distance) is kept much larger than
20 the spacing between the origination points or lenses, and the
21 inherently collimated beams are not focused, registration er-
22 ror at differing projection distances can be made negligible
23 and a semblance of infinite sharpness can be obtained.

1 (ii) amplitude-modulated spot with sweeping of a
2 combined beam — A device of this type should have true infi-
3 nite sharpness, since what is swept is a unitary beam (again
4 provided that the system does not bring the beam to a sharp
5 focus). Systems with this type of configuration and particu-
6 larly employing solid-state lasers are disclosed by Knize,
7 noted earlier, as well as U. S. Patents 5,534,950 to David E.
8 Hargis and 5,614,961 to Frank C. Gibeau, Ph. D. Amplitude
9 modulation in these systems is by electrical control of the
10 lasers.

11 It appears that these systems may have considerable prom-
12 ise, but are not to be found in the marketplace. It would
13 seem that for these devices with present-day available compo-
14 nents the laser power at certain needed wavelengths, or the
15 modulation response speed, or the overall economics, or combi-
16 nations of these considerations, are inadequate for realistic
17 commercial exploitation.

18
19 d) Line-scanning systems — The great bulk of reported
20 and patented developments in laser projectors is of this type,
21 using a separate acoustooptic modulator (AOM) for each primary
22 color. A seminal patent in the linewise AOM regime is U. S.
23 3,818,129 of Yamamoto, assigned to Hitachi. In such a system
24 each AOM is a crystal driven by an acoustic wave propagating

1 laterally (with respect to the laser-beam path) and modulated
2 by one video raster line at a time.

3 The compressions and rarefactions of this input modula-
4 tion in the AOM create or write a phase-retardation pattern
5 within the crystal, extending transversely from one side of
6 the crystal to the other and representing optical modulation
7 in one primary color for an entire video raster line. In the
8 most-advanced forms of these systems, just as the formation of
9 this retardation pattern is completed a laser is pulsed to
10 provide a light beam intersecting the pattern at right angles.

11 This reading-beam pulse length is very short compared
12 with the propagation speed of the acoustic wave through the
13 crystal, so that in effect the laser illumination is able to
14 stop the motion of the raster line. The laser beam in effect
15 reads the entire retardation pattern, and upon leaving the
16 crystal has impressed upon it — in phase retardation — a
17 latent image of the entire raster line.

18 This image is then developed, as suggested earlier, by a
19 polarization analyzer or equivalent, downstream of the crys-
20 tal. The result is an image of one primary color component of
21 the raster line, which is then preferably combined with like
22 images for the other two primaries, formed in separate AOMs.

23 At some point in the optical system, whether before or
24 after the modulation stage, each of the three individual pri-

1 mary-color laser beams or the composite beam must be shaped to
2 form a wide, shallow beam cross-section. For reasonable opti-
3 cal efficiency within the modulators it appears preferable to
4 use a more-common beam aspect ratio in passage through the
5 modulators — i. e., to perform the shaping after the beam has
6 passed through the modulators, though before the final projec-
7 tion lens. Considerable variation in such aspects of the
8 design, however, is possible.

9 The composite beam is enlarged and projected to a partic-
10 ular position vertically on a viewing screen, forming a three-
11 color raster line for viewing by the audience. The process is
12 repeated for successive lines — but shifting the vertical po-
13 sition progressively down the screen — to construct an entire
14 image frame, and then for subsequent frames to produce moving
15 pictures.

16 The vertical position for each raster line is controlled
17 by a rotating polygon or other vertical-sweep device, so that
18 successive lines are displaced to successive appropriate posi-
19 tions on the screen. This sweep, it is important to note,
20 follows the modulators — i. e. is introduced downstream,
21 along the optical path, from the modulators — as exemplified,
22 for instance, by U. S. 5,255,082 of Tamada, assigned to Sony.

23 Thus in AOM systems the slot-shaped beam is scanned or
24 stepped only on the projection screen, not on the modulators.

1 Though capable of moderately high contrast (over 300:1 in
2 certain military projectors), high resolution, reasonably good
3 color saturation, and infinite sharpness, this type of system
4 is subject to important limitations and also certain qualifi-
5 cations as explained below.

6 It appears that some of the largest and most sophistica-
7 ted corporate participants in the laser-projector race have
8 persistently placed their money — many millions of dollars of
9 it, over many years — on the acoustooptic modulator entries.
10 These include Sony, Schneider, TRW and IBM as well as a host
11 of lesser players.

12 For all that wagering, none of the AOM entries is seen to
13 place or even show, today. Many have dropped out entirely.

14 As suggested near the beginning of this "background" sec-
15 tion, resources invested in laser projectors have been wholly
16 disproportionate to performance. The question remains why
17 this pattern continues.

18 (i) light inefficiency and energy loss — This is
19 the dispositive consideration for AOM-based systems. Unfor-
20 tunately the compromises that enable achievement of the favor-
21 able parameters listed above also reduce, to an unacceptably
22 low level, the light efficiency of the modulators and the sys-
23 tem in general. The only laser projectors built in this way
24 that actually operated to produce excellent image quality were

1 military systems that required extremely large, high-power,
2 expensive lasers.

3 (ii) low bandwidth — Another element that suffers
4 in these systems is the capability to follow rapid action in a
5 scene. This may be related to persistence (or propagation
6 speed) in the AOM crystal, or the modulation constraints that
7 follow inherently from the need to refrain from outpacing the
8 pulsed-laser optical reading system.

9 (iii) complex optics — Many optical stages are
10 needed in an AOM system. The military projectors mentioned
11 above, though they operated continuously for two years and
12 always maintained certain military specifications of bright-
13 ness, resolution and contrast, had more than forty-five opti-
14 cal elements. Each optical surface attenuates undesirably.

15 (iv) stepped, slot-shaped beam — The special sig-
16 nificance of these features will be seen in later portions of
17 this document. For purposes of the present "background" sec-
18 tion, it suffices to point out that use of this type of beam
19 is required by, and directly associated with the nature of the
20 line-at-a-time modulator:

21 Since the modulator processes one raster line at a time,
22 the pulsed beam on which this modulation is impressed must
23 necessarily correspond in shape to the wide, shallow aspect
24 ratio of one raster line. It would not be possible to operate

1 a one-raster-line-at-a-time modulating system with any other
2 beam shape.

3 Similarly, it follows necessarily from the generation of
4 a complete raster line in optical form that the optical system
5 must include an optical stepper or continuous scanner of some
6 sort — to shift the target position successively down the
7 viewing screen for the successive raster lines, as described
8 earlier. Even a continuous scanner, in this type of system,
9 amounts to a stepper since the beam is pulsed only intermit-
10 tently, once per raster line. It would not be possible to
11 operate a one-raster-line-at-a-time modulating system without
12 some sort of stepper.

13 To the best of my knowledge it has not been reported in
14 the prior art that a slot-shaped beam, or a stepping system
15 for such a beam, might confer any other benefits upon a laser
16 projection system.

17
18
19 Now before going on from vector-, raster-, and line-scan-
20 ning (AOM) systems to take up systems that employ some very
21 different kinds of modulation, I shall pause and digress to
22 discuss some very important special considerations peculiar to
23 laser operation. As will be seen later, these are matters of
24 particular relevance to my invention.

1
2 e) Speckle — This well-known term describes a now-
3 familiar phenomenon of laser illumination, a coarse and very
4 bright granular pattern of light that shimmers with tiny move-
5 ments of the viewer's eyes. Speckle is highly undesirable in
6 image projectors for displaying ordinary pictures (movies,
7 television shows etc.) because it pervades the images and dis-
8 tracts from the informational or dramatic content of the show.

9 It has been explained to me that speckle is an interfer-
10 ence pattern formed within the eye. Although in principle
11 present with other sources too, speckle is not ordinarily
12 visible with such sources. Those skilled in the art recognize
13 that the speckle effect can be made negligible by introducing
14 various kinds of either phase confusion or relative motion, as
15 between the laser source and the eye.

16 Heretofore, however, actual equipment called into service
17 for accomplishing this has fallen far short of the elegant.
18 Many elaborate schemes of greater or lesser cost and complex-
19 ity are described in the literature.

20 One such "speckle eliminator", which is among the more
21 complex but demonstrates the seriousness of the problem, is
22 presented by Hargis, mentioned previously. Hargis introduces
23 several approaches, "each of which introduces an optical path

1 randomizing [medium] at an intermediate . . . plane within the
2 projection optics".

3 One of his systems is "a spinning diffusion plate" which
4 works at "transverse plate velocities in excess of a few cen-
5 timeters per second" but suffers from "transmission ineffi-
6 ciency (~50%), . . . large numerical aperture . . . and . . .
7 general bulkiness." Transmission is improved "to the 85%-95%
8 regime" by substituting "a thin sheet of wax supported between
9 glass plates."

10 Another system is a "flowing fluid diffuser" using "a
11 highly turbid fluid", suffering from "low transmission effi-
12 ciency with the inconvenience of a pump and associated plumb-
13 ing." A third, relying not on flow but on "Brownian motion",
14 Hargis rejects because "its transmission efficiency is lim-
15 ited, compared with what presently appears to be the best
16 available system described below".

17 His favored choice is a "novel nutating plate" which
18 "takes advantage of the desirable properties of wax laminate
19 diffusers". It involves a screen —

20
21 "supported on springs, and caused to vibrate in a plane
22 . . . perpendicular to the projection axis of the video
23 image beam . . . by orthogonal electromagnets

1 "Motion relative to two orthogonal axes is induced
2 in plate 25, together with a 90-degree phase shift be-
3 tween those motions, in order to avoid periodic moments
4 of zero velocity which would be associated with simple
5 harmonic motion along a single axis. The result is a
6 non-rotating diffuser which undergoes rapid nutation,
7 much in the manner of the contact surface of a[n] orbital
8 sander. Hence, all regions of the image are subjected to
9 the same motion. An excursion of 1 millimeter at 60 Hz
10 provides constant transverse velocity of about 20 cm
11 sec⁻¹. This yields an inexpensive device which is barely
12 larger in cross section than the imaging beam itself."

13
14 Provision of his illustrated device, plus a system of electro-
15 magnets and associated electrical drive, may not be expensive
16 but it is certainly elaborate and surely diffuses — and thus
17 randomly redirects and wastes — expensive laser energy.

18 Other workers have proposed a great variety of systems
19 (likewise severely overcomplicated, in most cases) for elimi-
20 nation of speckle. Representative are U. S. 5,272,473 teach-
21 ing a transducer that generates surface acoustic waves in a
22 projection screen, 5,506,597 proposing an array of mirror
23 cells movable between two positions in conjunction with a
24 magnifying element, 5,274,494 disclosing use of a Raman cell

1 to introduce optical sidebands, 5,233,460 counseling division
2 of laser light into three separate beams and introducing
3 differential delay or polarization rotation before recombina-
4 tion, 3,633,999 similarly advising a splitter to make many
5 separate beams whose speckle patterns mutually cancel, and
6 4,511,220 describing two polarizing beam splitters and a
7 totally reflecting right angle prism that form a composite
8 beam with mutually incoherent components.

9 Very generally speaking, speckle elimination systems of
10 which I am aware exhibit two common drawbacks. They add oth-
11 erwise unnecessary mechanical or electromechanical equipment,
12 and more importantly they subtract light.

13
14 f) Gamut and saturation — Patents and other technical
15 literature that touch on the selection of wavelengths for the
16 primary colors in laser projectors, by and large, have favored
17 color conventions or standards approaching those of commercial
18 broadcast television. The most important of these conventio-
19 nal wisdoms relates to selection of wavelengths for use as the
20 primary red.

21 It is well known that wavelengths close to the visible-
22 color chromaticity envelope provide the broadest and best base
23 for building a capability to display rich, saturated colors.

1 Nevertheless leading workers in the laser-projector field have
2 taught away from use of a long-wavelength red.

3 For example, U. S. 5,255,082 of Tamada, assigned to Sony,
4 strongly rejects use of laser lines in the region of 647 nm
5 for a primary red beam. Tamada offers the reasoning that such
6 wavelengths should be avoided because they are weak in the
7 spectra of certain lasers which he prefers.

8 Following suit is U. S. 5,136,426 of Linden, assigned to
9 Advanced Laser Projection. Linden warns that the —

10
11 "red light component produced by the krypton ion laser
12 requires four-to-five times the power as the comparable
13 power of an [argon] ion laser. . . . The krypton red
14 light component is at a wavelength that the human eye is
15 not as sensitive to and therefore makes it difficult to
16 balance with the other colors to give a complete color
17 scale with reasonable power.

18 "The [argon] ion laser in combination with a dye
19 laser is therefore preferred The dye laser pref-
20 erably converts light energy of a shorter wavelength to a
21 longer, tuneable wavelength."
22

1 Like other leaders in this field, Tamada and Linden counsel
2 use of wavelengths in the range of 610 nm for primary red,
3 generally based on rationales such as presented above.

4 It appears that one underlying motivation for such a
5 choice may have stemmed from the use of commercial video stan-
6 dards or conventions — NTSC, PAL or HDTV — which consis-
7 tently favor the 610 nm range. This historical choice, in
8 turn, appears to have arisen not truly because of apparent
9 luminosity to the human eye but rather from the limited
10 availability of television-display phosphors during early
11 color video development.

12 Another interesting historical development in the laser
13 projector field is the prevalent technique of filtering out
14 certain cyan lines that are present in popular lasers — par-
15 ticularly argon lasers, which are a good choice for providing
16 both blue and green lines. There seems to be a high likeli-
17 hood that the cyan light is discarded because it prevents
18 ready mixing of accurately neutral colors (black, white and
19 gray), as well as ideal rendition of all other colors — when
20 610 nm lines are chosen for the red primary.

21 The choice of laser light at 610 nm for red thus has com-
22 plicated repercussions — particularly since the cyan light in
23 an argon-laser beam amounts to some forty percent of the total
24 power or energy in the beam. Discarding that large fraction

1 of the beam power is a profligate waste, when a major chal-
2 lenge in the laser projector field is finding enough energy at
3 a reasonable price to form an adequately bright large image.

4 Whether because television phosphors lacked the capacity
5 for deeper red or because of their need for greater bright-
6 ness, present laser-projector workers stress the NTSC-based
7 luminance chart and the 610 nm red options — and thus forsake
8 the broader color gamut available in both film and computer
9 monitors, as well as the ample beam power readily available in
10 the cyan lines.

11 Some writings in the laser-projector field, such as the
12 Tamada and Linden patents, do at least mention the possibility
13 of longer-wavelength primary reds. All such writings are lim-
14 ited to either:

15
16 (1) use of such reds with acoustooptic modulators

17 (AOMs), or

18
19 (2) direct, electrical amplitude modulation of the
20 source lasers.

21
22 As will be seen, neither of these paths is part of the geneal-
23 ogy of my invention.

1 g) Laser types proposed or used — It is well known, at
2 least in concept, to employ lasers of a great number of dif-
3 ferent types for laser projectors. In particular it is known
4 to employ gas, dye and solid-state lasers in this field.

5 (i) gas — Many subtypes are known, but foremost in
6 this category are argon lasers for spectral-line groups in the
7 blue and green, and krypton lasers for red. Thus argon gas
8 laser beams are commonly split for separate modulation in
9 separate AOMs that receive blue and green image-data compo-
10 nents, while a krypton gas laser beam is modulated in a third
11 AOM that receives red image-data components.

12 These lasers are relatively straightforward to operate
13 and adjust. They require neither pumping nor tuning. They
14 require neither mixing nor frequency-doubling. Accordingly
15 they provide good efficiency as to both electrooptical energy
16 and human-operator efforts.

17 (ii) dye — In the opinions of many workers in this
18 field, dye lasers are of particularly great value because they
19 are tunable (particularly to 610 nm). In the opinion of this
20 writer, reliance on tunability is a handicap because of the
21 extra operator attention which it demands, as well as the high
22 cost of tunable mirrors and other needed paraphernalia.

23 Dye lasers are considerably less user-friendly than gas
24 lasers, on account of their requirements for management of an

1 additional pumping stage at the front end and mixing stage at
2 the back. In most cases they also consume profligate amounts
3 of extra energy in generating light at frequencies that are
4 not wanted but merely needed for purposes of subtraction or
5 addition to obtain desired frequencies.

6 This waste may be acceptable in high-end consumer or
7 boardroom equipment, where literally conspicuous consumption
8 can be a virtue. It is highly questionable, however, in a
9 cost-conscious commercial environment, for example a light-
10 hungry projector system for driving a monumental IMAX®-style
11 screen or an outdoor-spectacle system which projects images
12 onto, actually, monuments and other structures.

13 (iii) solid state — These devices may in the end
14 become the only sources that make economic sense, for use in
15 my invention as well as other types of systems. At the time
16 of writing, reasonable sources are available in red and green.

17 No adequate solid-state laser exists, however, for use as
18 a blue primary source in even a large consumer/boardroom unit.
19 Solid-state blue lasers adequate for use in large outdoor dis-
20 plays would appear to be at least some years in the future.

21 It is true that for such special applications a very
22 large number of individual very small solid-state lasers can
23 be ganged to amass a mighty beam. The overall economics (and

1 possibly ancillary procedures) of that approach appears unfa-
2 vorable relative to the present invention.

3
4 h) Liquid-crystal "device" modulators — Unlike the AOM,
5 a liquid-crystal "device" or "display" (LCD) modulator pro-
6 vides modulation over an entire frame. Here it is possible to
7 flood an entire frame at a time, and project the resulting
8 full frame to a projection screen or other viewing medium.

9 (i) some leading work in the field — Active cur-
10 rent effort on advanced LCD modulators that operate on un-
11 polarized beams is seen from researchers at Kent State Univer-
12 sity (see SMPTE Journal, April 1997). Earlier LCD efforts
13 correspond to U. S. 5,040,877 of Blinc, assigned to Kent
14 State; 5,517,263 of Minich, assigned to Proxima Corporation;
15 4,851,918 and 4,720,747 of Crowley, assigned to Corporation
16 for Laser Optics Research; and also 5,485,225 of Deter, as-
17 signed to Schneider.

18 (ii) visible electrode structure — All LCD modula-
19 tors are operated in transmission. That is to say, in such a
20 system a laser beam is projected completely through the entire
21 device from one side to the other.

22 All these devices accordingly require direct electronic
23 writing of the desired image electronically rather than opti-
24 cally — and this in turn requires one or another form of

1 multiple-electrode structure, in a pattern that is spread over
2 the entire frame. These electrodes are nominally transparent,
3 and indeed are not readily visible in displays of modest size,
4 such as for instance less than five feet along a diagonal.

5 In theater-size and larger formats, however, the elec-
6 trode edges are quite conspicuous. These patterns are dis-
7 tracting and intrusive, leaving LCD modulation essentially
8 unusable for high-quality imaging in theater and outdoor ap-
9 plications, unless all of the audience is at a very great dis-
10 tance from the screen or other projection medium.

11 (iii) no infinite sharpness — Also a drawback for
12 such large-scale applications is the fact that these LCD units
13 fail to preserve the laser property, described earlier, of
14 maintaining sharp imaging at widely varying projection dis-
15 tances. Various special-effects potentialities are thereby
16 foreclosed.

17
18 i) Liquid-crystal light valves — These liquid-crystal
19 light valves (LCLVs) are to be carefully distinguished from
20 the liquid-crystal display or device modulators discussed just
21 above. Whereas an LCD operates in transmission and requires
22 passing the projection beam through electrodes in the image-
23 writing (input) stage of the modulator, an LCLV operates in

1 reflection and has entirely separate image-writing and projec-
2 tion stages.

3 The image-writing stage may have electrodes, or may be
4 written optically or thermally, but all such activity is en-
5 tirely isolated from the projection stage by an opaque mirror.
6 There is one, unitary electrode in the projection stage but
7 its edges are ordinarily outside the image frame.

8 (i) development of the LCLV — Pioneering work with
9 LCLVs is due entirely to Hughes Aircraft Company and Hughes-
10 JVC Technology Corporation. This is seen in a series of pat-
11 ents extensively elaborating the LCLV and its usage in many
12 variants over two decades. These include U. S. 4,019,807 of
13 Boswell (1977), 4,127,322 of Jacobson, 4,343,535 and 4,378,955
14 of Bleha, 4,425,028 of Gagnon, 5,071,209 of Chang, 5,363,222
15 of Ledebuhr, 5,398,082 of Henderson, 5,428,467 of Schmidt,
16 5,450,219 of Gold, and 5,465,174 of Sprotbery (1995).

17 A particularly important precursor of the LCLV is attrib-
18 uted to Dr. Bleha. Particularly helpful expositions of the
19 working principles of these ingenious modulators appear in the
20 Boswell and Jacobson patents. Apparently an LCLV may be a
21 twisted-nematic type, a birefringent type, a hybrid of the
22 two, etc.

23 (ii) structure and operation of an LCLV — Common
24 to the several LCLV variants is a basic laminar configuration

1 in which an input or writing stage first develops a voltage
2 that varies spatially within the device frame, in accordance
3 with brightness variations that constitute an image to be
4 projected. An output or reading stage has a polarization-
5 influencing characteristic — such as a particular index of
6 refraction, corresponding to a particular optical phase delay.

7 The writing stage and reading stage are separated by an
8 opaque mirror, and the whole assemblage is sandwiched between
9 two transparent planar electrodes. By virtue of these elec-
10 trodes, voltages developed in the writing stage are applied to
11 the reading stage.

12 The spatially varying voltage induces corresponding spa-
13 tial variations in the polarization-influencing characteristic
14 of the reading stage. Meanwhile polarized light — the read-
15 ing beam — is introduced into the output or reading stage,
16 reflected from the internal mirror and returned toward the
17 projection screen.

18 The spatial variation in index causes the desired image-
19 brightness variations to be expressed as a spatially varying
20 polarization field, carried by the light beam leaving the
21 reading stage. As described earlier, this polarization field
22 is decoded or developed by a polarization analyzer so that the
23 beam carries a spatially varying intensity field, which is

1 perceptible to the eye as an image. For color images, this
2 strategy is replicated for each of three primary colors.

3 The resulting beam or beams are projected (with or with-
4 out combination into a common projection beam) in a substan-
5 tially conventional way through a projection lens to a viewing
6 medium. Whereas the writing stage may be excited with very
7 low-intensity light as for instance from a small CRT (or by
8 low voltages applied to an electrode matrix, or in other
9 ways), the reading stage is preferably excited with extremely
10 intense, projection-level illumination — such as, in the
11 Hughes work, a high-current arc lamp.

12 Evidently Hughes personnel have explored the use of LCLVs
13 with, exclusively, such incandescent sources ("white" light).
14 One reference, however, does propose the use of LCLVs with
15 laser sources — and that is not a Hughes document but rather
16 is the above-noted patent of Minich (Proxima). Both types of
17 usage are discussed below.

18 (iii) image projection using incandescent-lamp
19 sources — Regardless of other optical conditions, broad-
20 spectrum conventional light sources cannot provide the infi-
21 nite-sharpness characteristic. It goes without saying that
22 the Hughes projectors, operated as described in all the Hughes
23 patents, necessarily operate by actually focusing images on a
24 projection screen, with the associated shallow depth of focus.

1 Accordingly these systems are incapable of the earlier-men-
2 tioned special-effects applications that rely on infinite
3 sharpness.

4 (iv) full-frame — Most of the Hughes patents de-
5 scribe operation with the high-intensity "reading" or output
6 stage of the LCLV modulator flooded continuously by projection
7 light, or in other words all illuminated at once. This type
8 of operation offers a particularly appealing simplicity and
9 elegance: in essence the entire projection frame is opened
10 and held open, for whatever input may be written to the input
11 stage.

12 The output for regions of the frame that are not being
13 written, however, is simply dark. Thus for instance if a very
14 small but bright pen-light type of flashlight could be pointed
15 onto the writing stage and played about manually, presumably a
16 mammoth searchlight would appear to be — in real time — cor-
17 respondingly wandering about on the projection medium, which
18 might be for instance the exterior of a very large building.
19 Subject to contrast limitations, the projection medium would
20 be substantially dark in regions corresponding to writing-
21 stage regions not illuminated by the pen-light.

22 (v) poor energy economics, and brightness nonuni-
23 formity — The full-frame LCLV Hughes system is, however, sub-
24 ject to several drawbacks. First, per the above introductory

1 subsection on laser vs. nonlaser comparison, as in most other
2 projection systems the light from an incandescent source is
3 emitted in essentially all directions. Only a small fraction
4 of this omnidirectional radiation can be effectively captured
5 for guiding into the LCLV, and the remainder becomes a source
6 of heat-management problems.

7 Second, the light collected from a high-intensity source
8 is typically nonuniform across the frame in which that light
9 is collected. This too can be mitigated, and in conventional
10 ways including use of frosted (i. e., diffusing) elements —
11 but such solutions further scatter optical energy with only
12 limited directionality, and so inevitably further aggravate
13 the already unfavorable collection geometry. Special lensing,
14 too, may be used to reduce central bright spots, but at yet-
15 additional cost — both monetary and thermal.

16 Third, most writing stages operate incrementally — in
17 other words, based upon some sort of scanning input such as a
18 raster-driven or vector-graphics-driven spot of light, which
19 inherently can be active in only a very small portion of the
20 writing-stage frame at any given moment. The costly or even
21 precious high-power light beam, however, is directed indis-
22 criminate to the entire frame, including mostly unreceptive
23 regions that are not being written at any given moment.

1 This mismatch of written and read regions is mitigated by
2 the persistence characteristic of the LCLV — that is, the
3 continuing capability of a written region to pass reading
4 light, for a length of time perhaps equal to a tenth to a
5 fourth of the period of an entire frame, after the writing in
6 that region stops. Thus the unfavorable factor is not on the
7 order of thousands, only on the order of four or ten — but
8 still distinctly unfavorable.

9 Fourth, yet more energy loss is incurred in beam masking
10 to fit the image shape & projection frame. Whereas collection
11 systems typically yield beams that are circular, projection
12 frames are square or (particularly for widescreen movies)
13 rectangular.

14 In the case of masking down a circular beam 11 (Fig. 26)
15 to a square projection format 774, for example, the discarded
16 chordal areas 775 amount to about thirty-six percent of the
17 area of the circle — as is verified by simple arithmetic
18 later in this document. Thus 36% of the energy in a circular
19 beam is wasted in masking to a square frame.

20 Worse, in masking to a three-by-four screen format 874
21 (Fig. 27) the discarded fractions 875 come to 39%. In going
22 to the popular widescreen nine-by-sixteen format 974 (Fig. 28)
23 the lost fractions 975 are nearly 46%, close to half of the
24 optical energy in the circular beam.

1 (vi) polarization analyzer — Now turning from
2 energy losses somewhat in the direction of performance, the
3 intrinsic contrast ratio of an LCLV although high is far from
4 perfect, particularly since polarization extinction for broad-
5 spectral-band light is hard to control. (As noted previously,
6 the operation of polarizing devices is wavelength-dependent.)

7 Thus a perceptible glow may pass through an LCLV to the
8 projection medium in regions that should (based on the written
9 image) be dead black. In this way some of the costly optical
10 energy extracted from the omnidirectional source — and still
11 remaining after the several inefficient processes discussed
12 above — is used to illuminate areas that are dark in the de-
13 sired image.

14 (vii) vertically swept "slot" — Several of the
15 Hughes patents are direct testament to the intractable char-
16 acter of these problems. The above-mentioned Henderson,
17 Schmidt and Gold patents in particular lay out these same
18 difficulties and discuss a proposed solution.

19 Henderson teaches simply shaping of a white-light beam,
20 from an incandescent source, into a shallow slot-shaped beam
21 — and scanning that beam across an LCLV modulator. In this
22 case, since the light source itself is continuously operating,
23 a continuous sweep produces a continuum of overlapping succes-
24 sive beam positions rather than a discrete-stepping effect.

1 Henderson's goal is to greatly improve energy uniformity,
2 masking, read/write efficiency and contrast of an LCLV system
3 by placing the reading light in precisely the region where the
4 writing is taking place.

5 Evidently, as it appears, Henderson was not wholly suc-
6 cessful in this — since the companion Schmidt patent explains
7 at column 2 (lines 48 through 56), and also at column 9 (lines
8 30 and 46) that Henderson's approach, considered alone, suf-
9 fers severely from the loss of "telecentric behavior" of the
10 optical system, and also from chromatic aberration. Schmidt
11 notes that the purpose of his own invention is to restore
12 "telecentric behavior" and mitigate adverse chromatic effects.

13 A telecentric optical system is defined in the Gold pat-
14 ent as a system in which all "chief rays" are made to parallel
15 the optical axis of the system. A chief ray, in turn, is by
16 definition a ray that originates at an off-axis point of an
17 object or source and crosses the axis. Like chromatic aberration,
18 these are characteristics of conventional white-light
19 systems in which, for example, rays from various points of an
20 object which extends transverse to the axis are collected in a
21 lens and redirected — many typically crossing the axis — to
22 construct an image also transverse to the axis (but located at
23 another point along the axis).

1 Schmidt proposes resolving the Henderson problems through
2 particular forms of rotating polygonal deflectors that are
3 transparent, and ingeniously configured to preserve telecen-
4 tricity. Gold teaches use of a more conventional reflective
5 rotating polygon, but coupled with somewhat elaborate optical
6 elements to pre- and postcondition the slot-shaped beam for
7 deflection at the polygon — also to preserve (or restore)
8 telecentricity.

9 Despite these yeoman efforts, it appears that Hughes has
10 never used the scanning-slot system commercially. Not even
11 the most-recently introduced projector models — or technical
12 papers — from the Hughes development group suggest any move-
13 ment toward adoption of the Henderson/Schmidt/Gold system.

14 Perhaps this is due to the difficulty of forming a white-
15 light source beam into a very shallow, very wide slot-shaped
16 beam, without discarding so much light that the overall system
17 is unacceptably inefficient and impractical. Henderson, for
18 example, mentions (column 6, line 55) that brightness in at
19 least the vertical cross-section of the beam is Gaussian, and
20 suggests masking off a substantial portion of even that cross-
21 section to avoid using the skirts of the Gaussian beam. In
22 any event it seems that the scanning-slot beam — if not sim-
23 ply inoperative — was a dead-end side trip, in the course of

1 developments at the birthplace of the liquid-crystal light
2 valve.

3 (viii) image projection using laser sources — The
4 previously mentioned Minich patent proposes to use LCLVs with
5 laser sources — including red laser lines in the neighborhood
6 of 620 nm. Minich asserts that his LCLV-based apparatus is
7 "substantially similar . . . to the system [using a trans-
8 missive LCD modulator], except that the [LCLV] apparatus oper-
9 ates reflectively rather than transmissively."

10 By lumping these devices together somewhat indiscrimi-
11 nately, Minich suggests less than full appreciation for their
12 major differences. As mentioned earlier, the transmissive LCD
13 devices are objectionable for very-large-format projection be-
14 cause of conspicuous electrode patterns which they display.

15 Neither the problems of beam-shape matching and contrast
16 nor the possibilities of scanning slot-shaped beams are taken
17 up by Minich — in either his above-noted patent or his more-
18 recent one, U. S. 5,700,076. These problems are just as im-
19 portant with laser sources as with the Hughes white lamps.

20 Likewise the problem of speckle in systems using LCLV
21 modulators is never taken up by Minich in those patents. It
22 is substantially impossible to operate a laser/LCLV projector
23 without addressing this obstacle.

1 Minich furthermore fails to address the desirability of
2 infinite sharpness, although this represents a major applica-
3 tion for laser projectors. The conventional understanding is
4 that the image-forming mechanisms of LCLV modulators destroy
5 laser-beam coherence and thereby foreclose achievement of in-
6 finite sharpness.

7 Still further, in the patents mentioned above Minich says
8 nothing of the problems of brightness uniformity. Whereas
9 beam nonuniformity in white-light LCLV systems is significant,
10 in a laser-beam LCLV system it is of the utmost importance —
11 because laser beams are subject to a number of artifacts that
12 become plainly visible on the projection screen if a laser
13 beam is simply expanded to flood an LCLV reading stage.

14 To fill in certain portions of his disclosure, Minich re-
15 fers to documents of Texas Instruments Incorporated (column 5,
16 line 58) and of Hughes (column 9, line 58). The overall focus
17 of the Proxima development program, as suggested in the Minich
18 patent, is upon very compact, lightweight and inexpensive pro-
19 jectors that are very unlike the very large, high-quality
20 Hughes product (and two orders of magnitude lower in price).
21 Actual Proxima machines on the market appear to correspond to
22 the more-recently issued '076 Minich patent mentioned above,
23 not to anything in Minich '263.

1 All in all, it appears that the disclosures in the '263
2 Minich patent are conceptual rather than practical. It may
3 offer, as the foregoing enumeration of omissions suggests, a
4 less than completely enabling disclosure.

5
6 j) Marketplace considerations — The foregoing discus-
7 sion indicates some answers to the question posed earlier,
8 "why are large-screen laser projectors not common in the mar-
9 ketplace?" The answer is that numerous practical problems
10 attendant the real-world design and manufacture of a commer-
11 cially viable laser projector have not been answered.

12 One device that might provide a key to solution of some
13 of these problems — the liquid-crystal light valve — has not
14 been associated with laser projectors either in the market-
15 place or (notwithstanding the Minich '263 patent) in any mean-
16 ingful, practically oriented enabling publication. No product
17 or publication has revealed how to provide infinite sharpness,
18 or otherwise how to project images on irregular projection
19 surfaces having dramatically varying projection distances.

20 No teaching in the art has revealed how to defeat speckle
21 without adding elaborate equipment appendages that subtract
22 light. The art has never resolved, in marketplace terms, the
23 problems of brightness, contrast, energy efficiency, masking,

1 or illumination of nonwriting regions which Henderson, Schmidt
2 and Gold attempted to address.

3
4 As can now be seen, the related art remains subject to
5 significant problems, and the efforts outlined above —
6 although praiseworthy — have left room for considerable
7 refinement.

8
9
10 SUMMARY OF THE DISCLOSURE

11
12 The present invention introduces such refinement. The
13 invention has several independently usable facets or aspects,
14 which will now be introduced. Although these aspects are ca-
15 pable of use independently of one another — and as will be
16 seen they have distinct advantages considered individually —
17 for optimum enjoyment of their benefits the various aspects
18 are preferably practiced together in conjunction with one
19 another, and most preferably are all practiced together.

20 In preferred embodiments of a first of its independent
21 aspects or facets, the invention is a laser projector which
22 includes laser apparatus for projecting a picture beam that
23 includes visible laser light. The light is of wavelength
24 about six hundred thirty-five nanometers (635 nm) or longer.

1 Also included is a reflective liquid-crystal light valve for
2 modulating the beam with a desired image.

3 The foregoing may be a description or definition of the
4 first facet or aspect of the present invention in its broadest
5 or most general terms. Even in such general or broad form,
6 however, as can now be seen the first aspect of the invention
7 resolves certain of the previously outlined problems of the
8 prior art.

9 In particular my invention uses a liquid-crystal light
10 valve in conjunction with a laser operating wavelength region
11 that runs counter to all the conventional wisdoms discussed in
12 the background section of this document. By doing so, my
13 invention provides — and is the first to provide — a laser
14 projector that makes an energy-efficient, bright, rapid-motion
15 image with rich, full colors that are equal to or better than
16 the gamut and saturation produced by conventional motion-pic-
17 ture film projectors.

18 As mentioned earlier, except for some AOM systems the
19 wavelength region of choice has been about 610 nm — and AOM
20 systems are wholly unsatisfactory for the reasons described
21 earlier (inefficient use of light energy, low moving-image
22 bandwidth, and complex optics). Hence as a practical matter
23 it has been impossible or at least uneconomic to fully realize
24 the potential for good color gamut with such devices.

1 Evidently the 610 to 620 nm mind-set in this field has
2 been due to the familiarity of television images and the de-
3 sire to make images compatible with broadcast video, mitigate
4 brightness limitations, and mix good neutral colors after dis-
5 carding cyan lines from certain laser sources. The fundamen-
6 tal philosophy has been that laser projectors are competitors
7 of large-screen television sets.

8 Workers in this field are accordingly convinced that 610
9 nm red yields exciting, snappy, punchy colors. Actually, how-
10 ever, 610 nm corresponds to orange, or at most a red-orange,
11 and this choice prevents attainment of rich color. The rose
12 colors, deep reds and purples, and even a good honey color are
13 difficult to achieve if the red is not deeper. This is the
14 reason that red roses appear a banal orange-ish on television.

15 My invention proceeds from a contrary philosophy. The
16 fundamental objective of high-quality laser projector systems
17 should be image quality consistent with or better than film,
18 not broadcast television.

19
20 Although the first facet of my invention thus greatly im-
21 proves upon the state of the art, nevertheless I prefer to
22 practice this aspect of my invention in conjunction with cer-
23 tain other features or characteristics that optimize the bene-
24 fits of the invention. For instance I prefer that light which

1 appears red in the laser beam include substantially only the
2 laser light of wavelength about 635 nm or longer.

3 More particularly I prefer that the apparatus project a
4 beam of wavelength between about 635 and 650 nm. The most
5 highly preferred wavelength is about 647 nm.

6 Although my invention is fully capable of projecting
7 still images, I further prefer that the image be a moving pic-
8 ture. In addition I prefer that a projector according to this
9 aspect of the invention also provide green and blue laser
10 light — for mixing with the laser light of wavelength about
11 635 nm or longer to provide substantially pure neutral colors
12 including pure white and pure black. (Naturally the green and
13 blue are also used for other purposes.)

14 There may seem to be something of a semantic contradic-
15 tion in this concept of "pure black", as black is an absence
16 of all light and color. It may be hard to conceive how con-
17 trolling spectral content of light used in an image-forming
18 device can influence what is seen when all light is absent.
19 Since the era of oil paintings and throughout the age of color
20 photography and color lithography, however, achieving accurate
21 color balance "in the shadows" has been a mark of particular
22 excellence. Precise control of color in this difficult region
23 is an important figure of merit. Thus what is really at issue
24 is the capability of a color-reproduction system to represent

1 dark neutral colors, colors along the neutral axis of the col-
2 or-gamut solid, in the limit as the black pole is approached.

3 Preferably the laser apparatus projects substantially
4 cyan light with the blue or green light, or both. Heretofore,
5 as mentioned earlier in this document, cyan has been systemat-
6 ically removed from laser beams for image-projection use,
7 thereby both discarding a large fraction of the light power in
8 the beam and making the achievement of good whites and blacks
9 more awkward. In my present invention accordingly a very sig-
10 nificant increase in available beam power is enjoyed, while at
11 the same time color mixing is enhanced — not only along the
12 neutral axis or at the surface of the color-gamut solid, but
13 throughout — merely by refraining from exclusion of naturally
14 occurring cyan lines.

15 Some of my other preferences relate to speckle suppres-
16 sion, which will be discussed more fully below. At this
17 point, however, it bears mention that this aspect of my
18 invention preferably also includes some means for at least
19 partly suppressing visible speckle in such a picture.

20 The suppressing means preferably include apparatus for
21 displacing the beam during its projection, in conjunction with
22 the light of wavelength about 635 nm or longer. I have dis-
23 covered that this color is particularly beneficial in reducing

1 or eliminating speckle, when used together with at least
2 certain arrangements for beam displacement.

3 Even better is a combination of the 635 nm or longer
4 light with the cyan light mentioned above. I cannot explain
5 reliably why these wavelength combinations help suppress
6 speckle, but possibly the admixture of cyan — which cannot
7 interfere constructively or destructively with the other col-
8 ors — through a sort of spectral confusion tends to reduce
9 visible speckle. In any event I have observed the improve-
10 ment, and the validity of this preference in practice of my
11 invention does not rely on the correctness of my speculation.

12 Several preferences relate to modes of usage. I prefer
13 that apparatus of this first aspect of my invention also be
14 able to receiving high-bandwidth red, green and blue computer-
15 monitor signals from a computer; and that the projector thus
16 serve as a high-color-fidelity computer monitor. Preferably
17 the liquid-crystal valve is not controlled by light derived
18 from traditional or conventional broadcast video signals.

19 The liquid-crystal light valve is preferably controlled
20 by light or control signals applied to the valve by writing
21 onto a control stage of the valve:

22
23 a vector, bitmap or other computer file scanned from an
24 image or generated in a computer, or

1 amplitude-modulated laser-diode illumination swept two-
2 dimensionally across the control stage, or

3
4 images from a small transmissive liquid-crystal display
5 modulator, in turn written by signals not derived
6 from traditional broadcast video signals, or

7
8 other entire frames without interlace, or

9
10 a raster whose lines cross a short dimension of a picture
11 frame, or

12
13 motion-picture film color separations, or

14
15 a still image from a slide or overhead-projection trans-
16 parency, or a color separation made from such a
17 slide or transparency, or

18
19 a live image optically coupled, without electronic inter-
20 mediary, to the control stage.

21
22 Although the most highly preferred form of my invention
23 eschews use of broadcast video inputs, in another mode of use
24 of my invention preferably the light valve is controlled by

1 light substantially derived from a type of conventional or
2 traditional broadcast video signals. In this case it is pre-
3 ferred that substantially no color correction or gamma adjust-
4 ment be applied to remove the effects of using the 635 nm or
5 longer-wavelength laser light instead of broadcast video stan-
6 dard red.

7 This last-discussed preference is particularly interest-
8 ing in view of the previously described devotion to the 610 nm
9 regime, among prior artisans in this field. I have discovered
10 that 635 nm red is better even for display of traditional
11 broadcast video signals, and that no correction is needed.

12 I do, however, also prefer that — where the apparatus
13 also provides green and blue laser light — the proportions of
14 light power of the about 635 nm or longer-wave laser light,
15 the green laser light and the blue laser light be very roughly
16 eight to six to five (8:6:5). The 635 nm red laser light is
17 thus provided in greater proportion, and contrary to dire
18 earlier teachings I have found that this can be done in a
19 practical and economic way.

20 The first facet of my invention, still under discussion,
21 can be practiced in some very important alternative forms. In
22 one such form, for instance, every laser in the apparatus is
23 exclusively a solid-state laser. In another form every laser
24 in the apparatus is instead exclusively a gas laser.

1 Now turning to a second of the independent facets or
2 aspects of the invention: in preferred embodiments of this
3 second facet, my invention is a laser projector that includes
4 laser apparatus for projecting a picture beam along a path.
5 The beam includes laser light which tends to generate visible
6 speckle when used to form a picture on a projection medium.

7 The projector includes some means for at least partly
8 suppressing visible speckle in such a picture. For purposes
9 of generality and breadth in describing and discussing my
10 invention, I shall refer to these means simply as the "sup-
11 pressing means".

12 The suppressing means in turn include some means for dis-
13 placing the path during projection of the beam. Again for
14 generality I shall call these means simply the "displacing
15 means".

16 The foregoing may constitute a definition or description
17 of the second facet or aspect of the present invention in its
18 broadest or most general terms. Even in such general or broad
19 form, however, as can now be seen the second aspect of the
20 invention resolves the previously outlined problems of the
21 prior art.

22 In particular this aspect of my invention reduces speckle
23 without the primary drawback of prior systems — namely, ab-
24 sorbing or diffusing the beam. This second facet of my in-

vention thereby gains not only a significant advantage in the efficient use of optical energy but also substantially preserves a sort of collimation or pseudocollimation, which as will be seen has major advantages of its own.

Although this second facet of the invention as most broadly articulated represents a major advance in the art, to enhance its benefits I nevertheless prefer to practice this aspect of the invention in conjunction with certain other features or characteristics.

For instance I prefer that the projector further include a liquid-crystal light valve having a beam-modulation stage for impressing an image onto the beam; and that the displacing means scan the beam over this beam-modulation stage during projection. In this case it is also preferable that the displacing means scan the beam over the beam-modulation stage by mechanically or electrooptically deflecting the beam path rotationally.

For such purposes preferably the directing means comprise an optical deflecting element mounted for mechanical rotation. Still more preferably the deflecting element comprises a mirror mounted on a galvanometer or motor (such as for example a stepping motor). One additional detailed preference, most particularly applicable if the mirror is planar, is that the

1 mirror be mounted for rotation about an axis substantially in
2 a reflective surface of the mirror.

3 I also prefer to use this aspect of the invention with a
4 light valve which also has a control stage to control the "im-
5 pressing" function. In this case it is preferred that the
6 projector also include some means for writing an image incre-
7 mentally onto successive portions of the control stage; and
8 some means for controlling the displacing means in a special
9 way. These means respectively I shall call, for the reason
10 suggested earlier, the "incremental writing means" (or simply
11 "writing means") and "controlling means". The controlling
12 means operate to direct the beam onto successive selected por-
13 tions of the modulation stage, and to generally synchronize
14 the beam with the image-writing means.

15 The preferences stated in the preceding paragraph are
16 particularly beneficial. The controlling means provide the
17 beam displacement needed for reduction or elimination of
18 speckle — but yet their small cost and slight added complex-
19 ity need not be charged off to the achievement of speckle sup-
20 pression alone, since stepping a shallow beam, and synchroniz-
21 ing the beam with the image-writing process, has numerous
22 other important advantages.

23 I prefer that the control stage be a photosensitive stage
24 that receives an incrementally written optical image. Alter-

1 natively, however, for certain purposes the control stage in-
2 cludes an electrode matrix that receives incrementally written
3 electrical voltages.

4 I also prefer that the deflecting means be substantially
5 nondiffusing. Incorporation of such deflecting means, in the
6 writing and controlling means discussed above, produces a
7 remarkable benefit: the projector can be used in forming a
8 speckle-suppressed image on an irregular projection medium
9 that has portions at distinctly different distances from the
10 projector. In other words, the projector has speckle suppres-
11 sion in conjunction with the previously discussed capability
12 of infinite sharpness.

13 As is well known, the liquid-crystal light valve operates
14 by introducing at least partial disruption of the laser-light
15 coherence. This second aspect of my invention, however, nev-
16 ertheless preferably includes some means for projecting the
17 picture beam onto such an irregular projection medium.

18 Very surprisingly, the picture beam forms an image that
19 appears substantially sharp on the portions of distinctly dif-
20 ferent distances — notwithstanding the at least partial dis-
21 ruption of coherence. This extraordinary result is entirely
22 inconsistent with the conventional understandings in the art.

23 In particular, when I first proposed this preferred form
24 of the second aspect of my invention — to colleagues of ad-

1 vanced technical expertness in light-valve theory and opera-
2 tion — they advised me that the configuration would not re-
3 tain infinite sharpness. They explained that the reason was
4 that a liquid-crystal light valve (like a multimode optical
5 fiber, for instance) destroys the coherence of the beam.

6 I have demonstrated, however, that this configuration
7 does indeed achieve the infinite-sharpness characteristic. A
8 theoretical grounding for this result has since been suggested
9 to me. As I understand it, lasers have several special prop-
10 erties including not only coherence but collimation, although
11 these two properties are to a certain extent physically inter-
12 related and in most circumstances go hand in hand.

13 It appears that in my invention the phenomenon of infi-
14 nite sharpness arises — after spatial modulation of the laser
15 beam at the liquid-crystal light valve — in part because, as
16 I understand it, spatial modulation is preserved in the propa-
17 gating laser beam. This characteristic makes it possible to
18 project an image simply by projecting that beam, rather than
19 by refocusing an image from the light valve as with imperfect-
20 ly collimated nonlaser light.

21 The capability to preserve spatial modulation is in turn
22 attributable not to coherence but to collimation. In my in-
23 vention, since the beam is made to expand, collimation (paral-
24 lelism of rays) is not maintained literally. Nevertheless a

1 crucial characteristic of collimation is preserved: the rays
2 do not cross one another.

3 This property of noncrossing rays — which may be called
4 pseudocollimation or perhaps quasi collimation — still fur-
5 ther in turn, is maintained by the nondiffusing mirror or
6 other deflecting optics in the speckle-suppression aspects and
7 embodiments of my invention. Since the rays neither cross as
8 in a focal system nor become scrambled as in a diffuser, there
9 is no crosstalk between different portions of the image — or
10 in other words spatial modulation is preserved.

11 I wish it to be understood that the foregoing explana-
12 tions, which seem to account for successful infinite-sharpness
13 operation of my invention, merely represent efforts of others
14 to explain that success after the fact, and may be specula-
15 tive. The actual successful operation is itself a fact, not
16 dependent upon the validity of these explanatory efforts —
17 and of course the validity of my appended claims related to
18 this preference for the second aspect of my invention is not
19 to depend upon the correctness of these efforts.

20 An additional preference is that the displacing means be
21 substantially lossless, to within one percent of beam inten-
22 sity. Another preference is that the projector also include
23 beam-expansion means which cooperate with the displacing means
24 to achieve a net gain in light-energy efficiency.

1 In comparison with masking off original circular edges of
2 the laser beam, such a gain for a square image approaches
3 roughly fifty-six percent, and for a screen aspect ratio of
4 four to three approaches roughly sixty-four percent. For a
5 screen aspect ratio of sixteen to nine, the gain approaches
6 roughly eighty-three percent. (I say "approaches" because, as
7 will be seen, a tiny amount of energy is still lost to masking
8 at the extreme right and left ends of the frame.)

9 Also preferably the displacing means and beam-expansion
10 means cooperate to substantially eliminate initial nonunifor-
11 mity of brightness in the beam. The beam-expansion means may
12 take the form of, for example, entrance optics ahead of the
13 displacing means; these optics advantageously expand the ini-
14 tial laser beam to an optimum specialized shape for displace-
15 ment by the displacing means.

16 Furthermore I prefer that the laser apparatus include
17 optical means for shaping the picture beam to a shallow cross-
18 section; and that the displacing means also shift the picture
19 beam on the projection medium, during projection. The optical
20 means preferably take the form of plural lenses in series for
21 adjusting the beam dimension in two substantially perpendicu-
22 lar directions, or a curved mirror that forms part of the
23 displacing means.

1 Where a curved mirror is used, it advantageously shapes
2 the picture beam to a shallow cross-section. Preferably it is
3 mounted in a galvanometer movement, or mounted to a motor (or
4 otherwise equivalently mounted and driven in controlled oscil-
5 lation), to scan the shaped beam over the modulation stage.

6
7 Now turning to a third major independent aspect or facet
8 of my invention, preferred embodiments provide a laser projec-
9 tor that includes laser apparatus for projecting a picture
10 beam which in turn includes exclusively laser light. The pro-
11 jector also incorporates a liquid-crystal light valve having a
12 beam-modulation stage for impressing an image onto the exclu-
13 sively laser-light beam, and having a control stage, distinct
14 from the beam-modulation stage, to control the "impressing"
15 function.

16 In addition the projector includes some means for writing
17 an image incrementally onto successive generally slot-shaped
18 portions of the control stage — as before, called the "writ-
19 ing means" or "incremental writing means". The projector also
20 has some means for directing the exclusively laser-light beam
21 onto successive selected generally slot-shaped portions of the
22 modulation stage, and for generally synchronizing the exclu-
23 sively laser-light beam with the image-writing means — i. e.,
24 "directing and synchronizing means".

1 (An AOM-based system cannot answer to the above descrip-
2 tion, since the control and beam-modulation stages in an AOM
3 are in essence one and the same. Furthermore the writing
4 means in an AOM take the form of an acoustic driver which
5 neither writes nor reads successive portions but rather writes
6 to and reads from the entire modulator for each raster line.)

7 The foregoing may represent a description of definition
8 of the third aspect or facet of my invention in its broadest
9 or most general form. Even as couched in these broad terms,
10 however, it can be seen that this facet of the invention
11 importantly advances the art.

12 In particular, this aspect of my invention for the first
13 time obtains the optical-energy-saving and contrast-enhancing
14 benefits of synchronized write/read beams in conjunction with
15 laser light sources. These benefits have been proposed previ-
16 ously — particularly in the previously discussed Henderson,
17 Schmidt and Gold patents — in connection with broadband opti-
18 cal sources such as arc lamps, but as noted earlier it appears
19 that those schemes were not successful. It has never been
20 suggested heretofore that write/read synchronization might be
21 useful with lasers and light valves.

22 More specifically, the assumption (telecentricity) that
23 is the basis of the two later patents to Schmidt and Gold is
24 inapplicable as to lasers. If it had been obvious to solve

1 the problems inherent in the Henderson proposal merely by
2 substituting a laser for Henderson's arc lamp, then of course
3 Schmidt or Gold — or both — would have suggested doing so.

4 In the projector of this third major independent aspect
5 of my invention, preferably the laser apparatus initially pro-
6 jects the exclusively laser-light picture beam having substan-
7 tially all rays substantially parallel to a common optical
8 axis, with substantially no ray crossing the optical axis or
9 otherwise passing through the center of any aperture stop. My
10 preferred apparatus therefore has no telecentric zone. The
11 exclusively laser-light picture beam is not focused at or near
12 the directing means or the modulation stage, or elsewhere
13 within the laser projector.

14 Preferably the liquid-crystal light valve includes a
15 substantially distinct spatial portion for modulation of each
16 distinct spatial portion of the exclusively laser-light beam,
17 respectively — a condition that cannot be achieved with any
18 of the Henderson, Schmidt or Gold arc-lamp-based inventions.
19 Also preferably the projected beam has a cross-section that is
20 substantially uniform in intensity, rather than having a Gaus-
21 sian intensity distribution (as Gold states is present for at
22 least the vertical dimension of the slot). I say "substan-
23 tially" for reasons that will later become clear in conjunc-
24 tion with discussion of Figs. 25a and 29.

1 In practice of the third facet of my invention, I prefer
2 that substantially the entire cross-section of the exclusively
3 laser-light beam, with only negligible masking (preferably at
4 two very extreme edges only), be directed onto the successive
5 selected portions of the modulation stage. Other preferences
6 are that substantially each control-stage portion have a sub-
7 stantially corresponding modulation-stage portion; and in this
8 case that the directing-and-synchronizing means generally syn-
9 chronize selection of modulation-stage portions with writing
10 at corresponding successive control-stage portions, subject to
11 a delay generally equal to rise time in the modulation stage.

12 It is also preferable that the directing means comprise
13 an optical deflecting element mounted for rotation. In this
14 regard I most prefer to use a mirror mounted on a galvanome-
15 ter, or motor; however, in alternative preferred embodiments
16 the deflecting element comprises a mirror mounted on a rotat-
17 ing disc, or multiple mirrors mounted about a rotating disc.

18 More generally it is preferred that the directing means
19 include a mechanically rotated reflective or refractive ele-
20 ment; and that all dimensions of the exclusively laser-light
21 beam at the light valve be substantially unaffected by disper-
22 sion in the directing means, regardless of whether the element
23 is reflective or refractive — not possible with light from a
24 halide lamp, filament lamp, arc lamp or other fundamentally

1 incandescent source. In one preferable embodiment, the con-
2 trol stage is a photosensitive stage that receives an incre-
3 mentally written optical image.

4 In connection with this third aspect of my invention I
5 have certain preferences related to efficient and convenient
6 mechanical layout of the system. These preferences are par-
7 ticularly beneficial if the projector includes some means for
8 reflecting the beam from the directing means into the beam-
9 modulation stage and for transmitting the beam, after return
10 from the beam-modulation stage, to form a picture on a projec-
11 tion medium. In this case it is preferred that the laser
12 apparatus be generally disposed on a first level — while the
13 light valve, writing means, and reflecting-and-transmitting
14 means are generally disposed on a second level above or below
15 the first level. For optimum efficiency and convenience in
16 this form of my invention, it is especially preferable that
17 the directing means also transfer the beam from the first
18 level to the second level.

19 This preference is advantageous in that the directing
20 means do double duty as means for effecting the needed trans-
21 fer. More specifically, in this arrangement preferably the
22 directing means turn the beam from a path generally associated
23 with the first level to propagate in a direction generally
24 perpendicular to that path, toward the second level.

1 Still more specifically I prefer that the beam follow a
2 first, generally rectilinear path from a laser source to the
3 directing means; and then follow a second, generally rectilin-
4 ear path from the directing means toward the beam-modulation
5 stage. It is further preferable that the directing means also
6 turn the beam from the first path into the second path, thus
7 achieving greatly improved simplicity in layout, a minimum
8 number of lossy optical elements, and efficiency of use of the
9 several components. Preferably the first and second paths are
10 generally mutually perpendicular.

11
12 Now in preferred embodiments of its fourth major indepen-
13 dent facet or aspect, my invention is a laser projector that
14 includes laser apparatus for forming a picture beam that in-
15 cludes laser light. The laser apparatus produces an initially
16 substantially circular laser-light beam subject to nonuniform
17 illumination.

18 The projector also includes some means for transmitting a
19 beam out of the projector for viewing by an audience as images
20 on a substantially rectangular viewing screen. These means
21 may be called, for reasons as above, the "transmitting means".

22 Also included are some means for forming an illuminated
23 image on the substantially rectangular viewing screen. These
24 "image-forming means" operate by using the circular laser-

1 light beam without masking off significant fractions of the
2 laser-light beam. The image-forming means include:

3
4 means for reshaping the initially circular laser-light
5 beam to a shallow, wide laser-light beam, and

6
7 means for scanning the shallow, wide laser-light beam
8 over the screen.

9
10 The foregoing may represent a description of definition of the
11 fourth aspect or facet of my invention in its broadest or most
12 general form. Even as couched in these broad terms, however,
13 it can be seen that this facet of the invention importantly
14 advances the art.

15 In particular, this aspect of my invention substantially
16 eliminates masking losses, by fitting essentially all the
17 energy from the entire circular laser beam to a rectangular
18 image format. This is accomplished by forming the reshaped
19 beam that generally matches the width of the rectangular image
20 — and then sweeping this reshaped beam through successive
21 overlapping positions along the height of the image, so that
22 the aggregate of the continuum of overlapping shallow beams
23 matches the overall height.

1 Although the fourth major aspect of my invention thus
2 significantly advances the art, nevertheless to optimize en-
3 joyment of its benefits I prefer to practice my invention with
4 certain additional features or characteristics. In particu-
5 lar, I prefer that the projector further include some means
6 for minimizing the influence of nonuniformity of illumination
7 in the initially substantially circular laser-light beam.

8 Preferably these minimizing means include the reshaping
9 and scanning means, which operate in such a way as to tend to
10 cause the nonuniformity to average out. More specifically,
11 the reshaping means typically introduce additional illumina-
12 tion nonuniformity along the width of the shallow, wide laser-
13 light beam; and I prefer that the image-forming means further
14 comprise means for compensating for the additional illumina-
15 tion nonuniformity.

16
17 In preferred embodiments of its fifth major independent
18 facet or aspect, my invention is a laser projection system for
19 forming an image on an irregular projection medium having por-
20 tions at distinctly differing distances from the projector.
21 The system includes laser apparatus for projecting a picture
22 beam that includes laser light.

23 It also includes a liquid-crystal light valve for
24 impressing an image onto the beam; and some means for project-

1 ing the beam from the light valve, with the impressed image,
2 onto the irregular projection medium. The latter means I
3 shall call the "projecting means".

4 The foregoing may represent a description of definition
5 of the fifth aspect or facet of my invention in its broadest
6 or most general form. Even as couched in these broad terms,
7 however, it can be seen that this facet of the invention
8 importantly advances the art.

9 In particular, this aspect of my invention is the first
10 system of any raster type that forms a sharp image on a pro-
11 jection medium of the kind described. Indeed, heretofore the
12 only disclosed laser projector using a liquid-crystal light
13 valve is the previously discussed Minich patent 5,517,263 —
14 and that patent teaches nothing of imaging on such a projec-
15 tion medium.

16 That omission should be of little surprise, in view of
17 the previously mentioned belief among at least some experts in
18 liquid-crystal light valve theory. As noted earlier, that be-
19 lief is to the effect that such a light valve is incapable of
20 the needed "infinite sharpness" characteristic that would en-
21 able projection on irregular projection media as defined in
22 the above description of the fifth facet of my invention.

23 Although the fifth major aspect of my invention thus sig-
24 nificantly advances the art, nevertheless to optimize enjoy-

1 ment of its benefits I prefer to practice my invention with
2 additional features or characteristics. In particular, I
3 prefer that the irregular projection medium be one of these:

4
5 an interior of a dome, or other building having internal
6 surfaces that are not generally normal to a pro-
7 jection direction,

8
9 an exterior of a dome, sculpture, monument, or other
10 structure having external surfaces that are not
11 generally normal to a projection direction,

12
13 a waterfall,

14
15 a water fountain,

16
17 fog or a cloud,

18
19 ice,

20
21 a scrim in front of a curtain or screen,

22
23 a plurality of scrims in optical series,

1 one or more trees,

2
3 grass, vines or other foliage,

4
5 a hillside or other landscape, or other receding surface,

6 or

7
8 an array of people or other animals or other discrete

9 objects, or combinations thereof, at diverse

10 distances from the projecting means.

11
12 The fifth aspect of my invention as very broadly con-
13 ceived, and as set forth above, is for use with an irregular
14 projection medium of the character described. That is to say,
15 the irregular projection medium is simply a part of the con-
16 text or environment of the invention.

17 My invention as defined by certain of the appended
18 claims, however, also incorporates the irregular projection
19 medium as an element of my invention. This preferred form of
20 the invention, in which the projection medium is not merely
21 contextual but actually a part of the invention itself, is a
22 particularly powerful and unique system.

23 That system is in effect a combination of the laser pro-
24 jector of the fifth aspect of the invention with the struc-

1 tures of the variegated types discussed. As a conjunction of
2 my infinite-sharpness projector with specially selected or
3 assembled irregular projection media, this particular pre-
4 ferred form of my invention enables presentations of an extra-
5 ordinary and outstanding character.

6 For example, this form of my invention can be used to
7 create outdoor public spectacles in which literally many
8 hundreds of thousands of people view giant images projected
9 with sharp clarity upon massive surfaces. The surfaces may be
10 selected large buildings — whether skyscrapers, huge domes,
11 statues or monuments — or a natural canyon such as for in-
12 stance the walls of Yosemite Valley or even the Grand Canyon.

13 My invention is capable of throws on the order of kilom-
14 eters, still maintaining infinite sharpness, and (with very
15 large powerful lasers or ganged multiple lasers) image dimen-
16 sions the size of a football field. The images are not limi-
17 ted to vector graphics as in primitive laser shows, but can be
18 raster images including scenery, natural faces, action scenes
19 and anything else that can be made into a bitmap sequence or
20 otherwise displayable image.

21 Alternatively this form of the invention can create, for
22 extremely large audiences, special shows on the interiors of
23 large domes or other large irregular spaces such as the vari-
24 ous inside walls of a very large train station, opera house,

1 or stadium (including parts of the audience in the stadium).
2 Another fertile application is the presentation of outdoor
3 dioramas in which different portions of a show — again poten-
4 tially including faces, pictures of animals etc. — are pro-
5 jected on waterfalls, groups of people, trees or any other
6 symbolically or practically useful reflective medium, either
7 unitary or composite.

8 In implementing the fifth form of my invention character-
9 istically the liquid-crystal light valve operates by partial
10 disruption of laser-light coherence in the beam; and I prefer,
11 notwithstanding the partial disruption of coherence, that the
12 image appear sharp on the projection-medium portions of dif-
13 fering distances. I also prefer that the image appear sub-
14 stantially evenly illuminated, except possibly where light is
15 distributed over a receding surface.
16

17 In preferred embodiments of its sixth major independent
18 facet or aspect, my invention is a laser projector that in-
19 cludes a light source for forming a picture beam — and a mod-
20 ulator for impressing a latent image onto the picture beam.
21 It also includes a polarization analyzing cube for receiving
22 light from the modulator and developing the image.

23 This facet of the invention also includes some means for
24 projecting the beam, with the developed image, for viewing by

1 an audience. As before I shall refer to these means as the
2 "projecting means".

3 The foregoing may represent a description of definition
4 of the sixth aspect or facet of my invention in its broadest
5 or most general form. Even as couched in these broad terms,
6 however, it can be seen that this facet of the invention
7 importantly advances the art.

8 In particular, the use of an analyzing cube rather than a
9 polarizing-sheet-material analyzer or a dichroic analyzer is
10 advantageous because the polarization selectivity of a cube
11 analyzer is much sharper than that of the other types. Ac-
12 cordingly with this sixth facet of my invention the resultant
13 image contrast and resolution are superior to those available
14 heretofore.

15 Although the sixth major aspect of my invention thus sig-
16 nificantly advances the art, nevertheless to optimize enjoy-
17 ment of its benefits I prefer to practice my invention with
18 additional features or characteristics. In particular, I pre-
19 fer that the cube also supply the picture beam to the modula-
20 tor. Also preferably the light source comprises a laser,
21 which — among the many benefits discussed earlier — enhances
22 the sharpness of polarization sensitivity, since the cube can
23 be one particularly designed for operation in a very narrow
24 spectral band about the laser lines.

1 I further prefer that antireflective coatings be formed
2 on three cube faces through which the beam passes to and from
3 the modulator. Advantageously the cube has six faces, includ-
4 ing three through which the beam passes to and from the modu-
5 lator and three others; and light absorbers are at one or more
6 of the other faces.

7
8
9 All of the foregoing operational principles and advantag-
10 es of the present invention will be more fully appreciated
11 upon consideration of the following detailed description, with
12 reference to the appended drawings, of which:

13
14
15 BRIEF DESCRIPTION OF THE DRAWINGS
16

17 Fig. 1 is an isometric drawing — rather schematic and
18 not to scale — of a laser-projector optical system according
19 to a preferred embodiment of the present invention, using gas
20 lasers or alternatively solid-state lasers, or both;

21 Fig. 2 is a plan view of the upper level of the Fig. 1
22 embodiment, still not to scale but somewhat more realistic
23 than Fig. 1 as to proportions;

1 Fig. 3 is a like view of the lower level of the same
2 embodiment, but showing a variant optical train;

3 Fig. 4 is a left-side elevation, like Fig. 2 as to
4 accuracy of relative dimensions, of the same embodiment;

5 Fig. 4a is a face-on elevation of a liquid-crystal light
6 valve as used in the embodiment of Figs. 1 through 4;

7 Fig. 5 is an isometric drawing, conceptual and not to
8 scale, for a preferred embodiment of the invention related to
9 Fig. 1 and enlarged to show only the beam-scanning portion for
10 one color channel (e. g. red), using partly reflective and
11 partly refractive beam shaping — and showing the scanning
12 system at the top of its range;

13 Fig. 6 is a like view but showing the scanning system at
14 a different stage in the scanning operation, namely at the
15 center;

16 Fig. 7 is a like view with the scanning system at yet
17 another stage, namely the bottom;

18 Fig. 8 is an elevational optic diagram, showing the
19 optical path at the rotationally oscillating mirror of the
20 Fig. 1 through 6 systems unfolded — i. e., representing the
21 mirror only as a straight dashed line;

22 Fig. 9 is a plan view corresponding to Fig. 8;

1 Fig. 10 is a variant mirror that is curved in two or-
2 thogonal directions, to replace the mirror and two lenses in
3 Figs. 1 through 9;

4 Fig. 11 is an elevational view like Fig. 8, but using the
5 Fig. 10 rotating mirror in a variant primarily reflective beam
6 shaper (but still with at least one recollimating lens at the
7 modulator section of the system);

8 Fig. 12 is a plan view corresponding to Fig. 11;

9 Fig. 13 is a view like the upper portions of Figs. 5
10 through 7 but showing a stationary mirror and a nonmechanical
11 beam deflector;

12 Fig. 14 is a chromaticity diagram (after Judd and Wys-
13 zecki, Color in Business, Science and Industry, Second Edi-
14 tion, Wiley 1952, 1963) showing the wavelengths and chromatic-
15 ity positions of visible light wavelengths;

16 Fig. 15 is a conceptual system diagram showing the CRT-
17 driven Fig. 1 embodiment in block-diagrammatic form;

18 Fig. 16 is a like view of a related embodiment operating
19 from input-image information applied directly by sweeping am-
20 plitude-modulated laser-diode illumination two-dimensionally
21 across the control stage of a liquid-crystal light valve,
22 rather than through CRT means;

23 Fig. 17 is a like diagram showing a preferred embodiment
24 operating from input-image information applied directly by

1 illuminating the control stage of a liquid-crystal light valve
2 with images from a small transmissive liquid-crystal display
3 modulator;

4 Fig. 18 is a diagram like Fig. 15 or 16 but showing a
5 different preferred embodiment operating from noninterlaced
6 input-image information such as a vector, bitmap or other
7 computer file scanned from an image or generated in a com-
8 puter, and written electronically to the control stage of a
9 liquid-crystal light valve;

10 Fig. 19 is a like diagram showing still another preferred
11 embodiment operating from input-image information in the form
12 of a nonincrementally written still image;

13 Fig. 20 is a like diagram showing yet another preferred
14 embodiment using input-image information in the form of nonin-
15 crementally written motion-picture film color separations;

16 Fig. 21 is a like diagram showing yet another embodiment
17 using input-image information in the form of live images ac-
18 quired and written without electronics, optically, to the
19 light valve — and also projected — all in real time with no
20 need for storage;

21 Fig. 22 is a timing diagram showing synchronization in
22 the Fig. 19 embodiments, particularly with delay to accommo-
23 date rise time in a liquid-crystal display;

1 Fig. 23 is a simplified optical diagram showing two coop-
2 erating principles of operation of a speckle-suppression sys-
3 tem that is incorporated into certain preferred embodiments of
4 the invention — particularly with the system in one stage of
5 its operation;

6 Fig. 24 is a like view showing the same system in another
7 stage of its operation;

8 Fig. 25 is a diagram showing some representative distri-
9 butions of illumination across a laser beam cross-section, for
10 comparison with an idealized distribution also shown;

11 Fig. 25a is a like diagram showing very schematically or
12 conceptually another representative laser-beam intensity dis-
13 tribution, which I prefer to use with preferred embodiments of
14 my invention;

15 Fig. 26 is a diagram showing needed masking for a prior-
16 art system using a circular light beam and a square projection
17 screen;

18 Fig. 27 is a like diagram for a screen with 4:3 aspect
19 ratio;

20 Fig. 28 is a like diagram for a screen with 16:9 aspect
21 ratio;

22 Fig. 29 is a group of coordinated diagrams, the first
23 showing in elevation an intensity distribution related to that
24 of Fig. 25a, still very conceptually, and also conceptually

1 showing conspicuous irregular intensity nonuniformities such
2 as are typically found in a laser beam if used in a polariza-
3 tion-driven light valve; and the remaining diagrams showing
4 the shape relationship between an original circular laser
5 light beam and a very shallow reshaped beam for scanning over
6 a projection screen, in the efficiency- and uniformity-in-
7 creasing system of the present invention; and also showing the
8 illumination distribution in the reshaped beam, and showing
9 residual correction factors that can be required or desirable
10 (or superfluous) in both cases;

11 Fig. 30 is a group of very simplified coordinated dia-
12 grams (a side elevation at top right, plan at bottom right,
13 and viewer's perspective at left) showing in a somewhat fan-
14 ciful way the imaging capabilities of a system according to
15 the invention as used with an irregular projection medium
16 comprising the exteriors of various buildings or other struc-
17 tures including a dome, in accordance with the invention, and
18 particularly relative to disrupted coherence;

19 Fig. 31 is a like set of diagrams (side elevation at top,
20 plan at bottom) for another type of irregular projection medi-
21 um that comprises the interior of a dome;

22 Fig. 32 is a thumbnail sketch that is a like view but
23 even more fanciful and with another type of irregular projec-
24 tion medium that includes a waterfall or fountain, or both;

1 Fig. 33 is a like view with another type of irregular
2 projection medium including plural scrims behind a theater
3 proscenium;

4 Fig. 34 is a like view with yet another type of irregular
5 projection medium comprising foliage; and

6 Fig. 35 is a like view with still another type of irregu-
7 lar projection medium comprising arbitrary assemblages of
8 discrete articles, including creatures.

9
10
11 DETAILED DESCRIPTION

12 OF THE PREFERRED EMBODIMENTS

13
14 a) Overall configuration — Preferred embodiments of my
15 invention, by assigning multiple tasks to certain key ele-
16 ments, achieve the remarkable imaging and energy-usage char-
17 acteristics described above. They also achieve a degree of
18 simplification and a minimal number of optical surfaces not
19 previously attainable.

20 Laser-projector apparatus is advantageously laid out in
21 two levels or tiers, one above the other. Either level can be
22 used for the sources 10 (Figs. 1-4), and the other for the
23 modulation and projection subsystems 23-44, but I prefer to
24 put the sources on top. This configuration is particularly

1 beneficial in allowing very easy exchange of the lasers, for
2 use in image shows calling for higher- or lower-power beams.

3 Such interchange often demands a change of projection
4 lens 44, too. The lens, however, is generally well forward of
5 the lasers and therefore accessible regardless of the level on
6 which it is mounted.

7 The suffixes "r", "g" and "b" on the numbered elements in
8 the drawings represent corresponding components in the red,
9 green and blue channels respectively. Those who are familiar
10 with the art will best understand the layout and operation of
11 my invention from the fact that I constructed the illustrated
12 prototype from a conventional arc-powered Hughes projector —
13 but with the usual source system, dichroic spectral splitters,
14 stationary steering mirrors, and polarizer-analyzer elements
15 removed, and most projection optics replaced.

16 The blue and green beam 11gb is split at a dichroic
17 separator 12gb to form respective beams of green 13g and blue
18 13b, which traverse plane mirrors 14, 16 to reach their nega-
19 tive lenses 18g, 18b. The two-mirror dogleg path 13g-15g-17g
20 is not strictly necessary but only included for convenience
21 and to facilitate placement of the lasers more compactly for-
22 ward above the modulation stages.

23 Transfer of the laser beams from the upper level to the
24 lower — together with a change of direction that is needed

1 for entry of the laser beams into the modulation subsystem at
2 right angles to the final projection path — is accomplished
3 by small folding mirrors 20 that also serve in speckle sup-
4 pression, circular-to-rectangular beam shaping, and brightness
5 and contrast enhancement. For these latter purposes the pla-
6 nar mirrors 20 are preceded by respective negative lenses 18
7 and cylindrical lenses 19, and are mounted to drivers 21 for a
8 small angular oscillatory rotation.

9 Each driver is preferably a galvanometer movement but may
10 instead be a motor, stepping motor, solenoid driver, piezoele-
11 ment, pneumatically driven reed, or other suitable equivalent.
12 As noted earlier, beam deflection alternatively may be accom-
13 plished with spinning polygon mirrors or other known devices.

14 (If preferred to eliminate the two dogleg bounces 14g,
15 16g, the argon laser 10gb can instead be shifted to a position
16 in line with the multipurpose planar folding mirror 20g in the
17 green channel. That mirror with its entrance optics 18g, 19g
18 is then reversed in orientation, and the angles of the separa-
19 tor 12gb and deflector 14b adjusted to compensate.)

20 The beams from the mirrors proceed through lenses 23 into
21 the entry faces 24 of polarizer-analyzer cubes 25. Each cube
22 is made of two forty-five-degree right prisms, one of which
23 has a polarizing dichroic layer 26 coated on its hypotenuse —
24 i. e., at the interface of the two prisms.

1 As mentioned earlier, such a cube provides relatively
2 very sharp polarization discrimination, and thereby improved
3 image contrast and sharpness relative to Polaroid® material or
4 stand-alone dichroic polarizers. In my invention, however,
5 this function is not operative with regard to the beam enter-
6 ing downward through a top entry face 24. Because the polari-
7 zation of our laser beams is typically even sharper than the
8 discrimination capability of the cube, ordinarily the central
9 polarizing layer 26 instead has substantially no effect on the
10 polarization state at this point.

11 The polarizing layer therefore simply deflects the down-
12 ward-incoming beam at ninety degrees and out through the rear
13 face 27 into the front or reading stage of the liquid-crystal
14 light valve modulator 30. In my prototype the rear stage of
15 each modulator 30 is written by an input image that is coupled
16 through a fiber-optic or preferably lens-system matcher 31
17 from a respective infrared cathode-ray tube 32. The image
18 signal for the CRT 32 is provided through cables 33 from a
19 conventional source — either computer video or conventional
20 broadcast video, or virtually any other source if the system
21 is suitably configured for the corresponding form of data.

22 The liquid-crystal light valve 30 may be substantially
23 conventional, or of a type not yet known. As mentioned earli-
24 er, several variant kinds of these valves have been described

1 and are available. Each valve has a rectangular image frame
2 (Fig. 4a).

3 In general the function of the valve 30 includes receiv-
4 ing a consistently polarized picture beam or reading beam from
5 the rear, output face 27 of its cube 25, and reflecting the
6 beam at an internal mirror within the valve. (The previously
7 mentioned Hughes patents describe in great detail the inner
8 features and workings of several different valve types.) The
9 valve thereby returns the reading beam forward into the face
10 27 from which it came. In the process, the valve introduces
11 into the reading beam a variable delay — and therefore vari-
12 able polarization state — which correspond at each point in
13 the frame to writing-light intensity, modulation-voltage lev-
14 el, or other type of control stimulus in the control or writ-
15 ing stage of the valve 30.

16 The beam reentering the cube face 27 thus has read, or
17 has had impressed upon it, a latent image expressed in polar-
18 ization state. In at least some types of liquid-crystal light
19 valve, the polarization state at each point in the image frame
20 can be described as a rotation that is related to the inten-
21 sity of the writing image (or control voltage etc.) at the
22 corresponding point.

23 Upon reaching the analyzing layer 26 within the cube, the
24 beam is in effect decoded: light polarized in the original

1 polarization plane is deflected back up, generally toward the
2 multipurpose mirror 20, and thus discarded — while any light
3 polarized at ninety degrees to the original plane passes
4 through the dichroic layer and out the forward face 35 of the
5 cube and into the projection subsystem proper. The latent
6 image 34 component of each primary color is thus developed and
7 forwarded for projection.

8 The three primary image components 34r, 34g, 34b are next
9 combined by a turning mirror 37r and dichroic filters 39gb,
10 41gb to form a unitary full-color image beam 43. A projection
11 lens 44 controllably expands — but does not focus — this
12 optical signal to provide an expanding beam 45 for propagation
13 to a projection medium.

14 b) Color gamut and saturation — The lasers include a
15 red source 10r in the form of a krypton-gas laser, most pref-
16 erably emitting red light in the 647 nm region. While this is
17 the ideal, I prefer to use laser spectral lines that are be-
18 tween 635 and 650 nm, or at least are above 635 nm; these are
19 far superior to the 610 nm conventional preference, or the
20 approximately 620 nm indicated in the Minich patent for use
21 with liquid-crystal modulator types.
22

23 Wavelengths at 647 or at least above 635 nm are capable
24 of forming rich colors on the projection medium, equal or fa-

1 vorably comparable with those of projected images from film —
2 which as noted earlier is the appropriate standard of compari-
3 son for the image quality produced by my invention. Deep red
4 roses, deep red football uniforms, deep red sunsets, and vivid
5 purples as seen using my invention are actually deep red and
6 purple, not merely the gaudy orange or red-orange seen with
7 610 nm systems.

8 Also included in my apparatus is a green and blue source
9 10gb. This is preferably implemented as an argon-gas laser
10 emitting green and blue light in the regions below roughly 540
11 and 490 nm respectively.

12 All three wavelength regions are in essence chosen for
13 their capability to provide well-saturated colors not only
14 when appearing in pure form but also when mixed; and the rel-
15 ative intensities mentioned earlier are preferred for the ca-
16 pability to mix to good neutral whites, grays and blacks when
17 needed. The ability to yield good saturation relates to the
18 positions of these particular wavelengths along edges and very
19 near the corners of the familiar chromaticity diagram (Fig.
20 14) .

21 Intermediate wavelengths representing cyan are preferably
22 retained in the blue-green beam 11gb. Light in this range is
23 somewhat divided at the dichroic separator 12gb between the
24 two separated primary channels 13g, 13b.

1 These wavelengths seem to mix particularly effectively
2 with reds in the range just above 635 nm, producing not only
3 better neutral whites and grays but also enhanced flesh tones
4 and earth colors. Furthermore as discussed earlier they help
5 to suppress visible speckle, and they carry a large fraction
6 of all the power in the original argon laser beam — which
7 thus in my invention need not be discarded.

8
9 c) Beam-shaping and steering — Preferred forms of the
10 invention provide one or more optical components that reform
11 the round-cross-section laser beam into a wide, shallow slot-
12 shaped beam (for several different beneficial uses, as de-
13 scribed in subsection "e" below), and turn that beam from the
14 source tier of the apparatus downward into the modulation
15 subsystem. These shaping and steering functions may be accom-
16 plished with various sorts of devices:

17 (i) refractive/reflective — My present prototype
18 employs a combination of optical elements. First the laser
19 beam 11 enters a negative lens 18.

20 This first lens causes the exiting beam to slightly ex-
21 pand (Figs. 5-7), in all transverse directions, while propa-
22 gating. It is helpful to consider this process in only the
23 vertical plane (Fig. 8, in which the dashed line 20 represents
24 the planar folding mirror 20, and the optical path is shown

1 unfolded). The vertical expansion is at such a rate that,
2 upon reaching its cube 25 and modulator 30, the height of the
3 beam 51, 53, 54 will correspond to several raster lines 55-57
4 of the input image — or in any event a region tall enough to
5 encompass the height of the persistence zone 59 of the writing
6 mechanism 58.

7 In other words the negative lens 18 causes the beam to
8 follow an envelope that expands symmetrically (i. e., not ana-
9 morphically), so that all the previously collimated rays now
10 progressively and slightly separate from one another. The
11 speed of this expansion is determined so as to satisfy the
12 stated height criterion at the modulator.

13 Next a circularly cylindrical lens 19, while leaving the
14 vertical expansion substantially undisturbed, superimposes an
15 additional somewhat steeper horizontal expansion, best seen in
16 the horizontal plane (Fig. 9). This expansion, as well as the
17 resulting composite effect of the two lenses 18, 19, is of
18 course distinctly anamorphic. The circular-cylindrical optic
19 is selected to provide just enough horizontal expansion that
20 — again upon reaching the cube and modulator — the width of
21 the beam 51, 53, 54 will substantially just very slightly
22 overfill the frame width EE (Fig. 4a) of the liquid-crystal
23 valve.

1 These two elements 18, 19 thus complete the reformation
2 of the beam into a wide and shallow shape that has been spe-
3 cifically optimized for the processes that follow. The small
4 planar mirror 20 then turns the reformed beam (still expanding
5 anamorphically as it proceeds) downward 22. In this form of
6 the invention the two lenses 18, 19 constitute the previously
7 mentioned beam-expanding means. As previously suggested, rays
8 in the beam while separating from one another do not cross one
9 another or become scrambled, and thus may be described as
10 pseudocollimated.

11 This progressive separation continues until the beam
12 reaches the recollimator 23, which halts the expansion in at
13 least one direction — passing a substantially recollimated
14 beam to the cube 25 and modulator 30. Ideally, taking into
15 account the above-described character of the beam 22, this
16 calls for an anamorph 23. Residual anamorphism and other im-
17 perfections in the beam, however, can be trimmed in a later
18 lens 26, although I consider this stage somewhat optional.

19 From what has been said above, it will be apparent to
20 those skilled in the optical arts that any effort to accom-
21 plish these same goals with light of broad spectral bands as
22 proposed in the Henderson patent must face great obstacles.
23 The overriding objectives are defeated if the overall beam
24 cannot be restored to a semblance of collimation. Even the

1 very sophisticated solutions of Schmidt and Gold evidently
2 were not enough to overcome all the obstacles. With much more
3 nearly monochromatic laser beams, the problems are tractable.

4 As mentioned earlier in this section, the mirror 20 not
5 only turns the beam but also oscillates 20' rotationally about
6 a horizontal axis, and so sweeps the beam 22 forward and back
7 over the recollimator 23 and over the entry face of the cube
8 25. After reflection at the polarizer/analyzer layer 26, so
9 that the beam is again propagating horizontally, this back-
10 and-forth displacement of the beam path amounts to sweeping
11 the beam up and down the image frame of the modulator 30.

12 That is, the beam is continuously shifted or successively
13 stepped without overlap from positions 54t (Fig. 5) at top of
14 the image frame, through positions 54c (Fig. 6) at center of
15 the frame, to positions 54b (Fig. 7) at bottom. Correspond-
16 ingly, after passage through the projection lens 44, the wide,
17 shallow slot-shaped projection beam 45 sweeps from topmost
18 through central to bottommost positions 46t, 46c, 46b on the
19 projection medium 47.

20 Although for simplicity all this is illustrated with a
21 flat screen 47 at right angles to the projection axis, it will
22 be understood that the same operation holds true for irregular
23 projection media. This point will be discussed further in
24 later portions of this document dealing with such media.

1 The foregoing steering and shaping subsystem works well
2 in my prototype, and is implemented using components that are
3 simple, inexpensive and off-the-shelf. As will be discussed
4 in a later subsection of this document, however, the slot-
5 shaped beam that results does have significant nonuniformity
6 of brightness along its length (i. e., from side to side along
7 the horizontal extent of the beam).

8 Effective compensation of the nonuniformity is desirable
9 and preferable for best image quality. This nonuniformity can
10 be corrected by substituting a differently shaped optic — for
11 instance perhaps an elliptically or hyperbolically cylindrical
12 lens, or possibly an entirely custom-designed shape — in
13 place of the circular cylinder 18.

14 (ii) all reflective — The system of Figs. 5-12
15 does, however, require two refractive optical elements and a
16 total of five optical surfaces with the attendant adjustment
17 demands and energy losses. For high-volume manufacture of my
18 invention it would be worthwhile to consider preparation of a
19 single optic 120 (Fig. 10) that could accomplish the same
20 purposes with just one surface, and that a low-loss reflective
21 surface.

22 This optic is a curved astigmatic or anamorphic mirror
23 having one relatively more weak or gradual curvature 120e
24 about a generally horizontal axis, and another sharp curvature

1 120d about a generally vertical axis. This mirror might ad-
2 vantageously be cast, for example in epoxy, and then silvered.

3 Analogously to the refractive/reflective system, this
4 mirror would spread the beam 122 gradually (Fig. 11) in the
5 vertical plane and more steeply (Fig. 12) in the horizontal.
6 The single mirror 120 would thereby yield an output beam 122
7 with a shallow elongated output cross-section 151 — similar
8 to the beam 22 in the prototype system.

9 For best results, however, the shape should not only
10 spread the circular input beam 11 anamorphically as with the
11 two lenses discussed above, but also should trim the distribu-
12 tion of the rays to at least approximately equalize intensity
13 along the length of the shallow, elongated beam. Possibly
14 such an optic may introduce aberrations of shape that require
15 compensation in the recollimator 123.

16 The mirror 120' is to be mounted for oscillatory rotation
17 120', very generally as described above for its planar coun-
18 terpart 20. With a curved mirror, care must be exercised in
19 positioning the rotational axis relative to the mirror shape,
20 to minimize undesired small effects on beam direction or
21 movement at the modulator. Some small movements, as noted
22 earlier, are beneficial.

23 (iii) without moving parts — Still another solu-
24 tion to the shaping and steering functions is an electrically,

1 magnetically or piezoelectrically controlled cell 61 (Fig. 13)
2 in conjunction with a mirror 20, 120 that is fixed rather than
3 oscillating. The mirror may be planar, necessitating addi-
4 tional optics similar to the previously discussed lenses 18,
5 19; or may be specially formed (Figs. 10-12).

6 Various control devices such as Pockels or Kerr cells may
7 be usable for such a system. Typically the performance of
8 these devices is strongly wavelength dependent; however, this
9 characteristic once again represents little or no obstacle
10 since laser beams are more nearly monochromatic than arc lamps
11 and like broadband spectral sources.

12 Although vibration and wear have not posed problems with
13 my prototype, yet in principle over a period of time the os-
14 cillating mirrors 20 may give rise to significant maintenance
15 demands. Nonmechanical sweep systems such as introduced here
16 may therefore prove superior for at least some applications.

17
18 d) Image input — As mentioned earlier, my invention is
19 amenable to a great many different ways of writing images to
20 the liquid-crystal light valves. Certain of the appended
21 claims encompass preferred forms of my invention that include
22 some of these diverse writing modes, which are briefly dis-
23 cussed below.

1 (i) cathode-ray tubes — This approach most closely
2 approximates the writing system of the Hughes projectors, us-
3 ing a small infrared CRT 32 in each color channel to write the
4 image to the photosensitive rear stage of the light valve. In
5 my prototype the light valve, coupler, CRT and input-signal
6 cabling — as well as the bottom case — are all essentially
7 standard components of a Hughes projector, for instance Model
8 D-ILA.

9 There is, however, an important difference: I prefer to
10 feed all input-image signals 60 (Fig. 15) to the CRTs 32
11 through an electronic apparatus known as a line doubler, par-
12 ticularly Model QD 7000, of the QD Technology company, Fremont
13 California. The line doubler performs very useful functions,
14 particularly important when using conventional broadcast video
15 signals: (1) separating 62 the color channels to isolate the
16 red, green and blue image components, and (2) interpolating
17 additional raster lines between the lines of the original im-
18 age data, and (3) providing a reformatted all-digital output
19 63 to each CRT. The device also provides a so-called "image-
20 enhancement" function for any video feed.

21 Interpolation is important because many conventional sig-
22 nal formats provide a relatively coarse raster spacing that is
23 conspicuous and distracting when greatly enlarged. In the
24 context of my invention the original coarse raster would be

1 particularly objectionable because it is more pronounced when
2 formed by a sharp, high-contrast laser projector.

3 The line doubler can accept a variety of input-signal
4 formats, including various conventional broadcast signals and
5 computer-style video data. The doubler also incorporates con-
6 venient features such as facilitating audio management.

7 The doubler directs each reformatted image-data set 63 to
8 the corresponding CRT 32 in the form of an amplitude-modulated
9 data stream 33, synchronized with two-dimensional sweep sig-
10 nals 64 that control the vertical and horizontal position of
11 the CRT electron beam. These sweep signals 64 (most partic-
12 ularly the vertical-advance signals) are also synchronized 65
13 with one-dimensional sweep of the high-power laser beam 11, 22
14 (Fig. 15) by the oscillating mirror 20.

15 Each CRT optical output (or output coupler) 31 writes the
16 image to the corresponding modulator 30, which simultaneously
17 receives the swept beam 22 and produces a high-power output
18 beam 34 for combination and projection 44 as a unitary beam 45
19 to a projection medium 47.

20 If a fiber-optic light pipe is substituted for the lens
21 system 31 used as a coupler, the light pipe must be made with
22 extremely fine fibers for applications involving very large
23 projection screens, to avoid image granularity (in effect a
24 type of pixel structure) under the associated conditions of

1 very high enlargement. If a conventional lens arrangement is
2 used to relay the CRT image to the writing stage of the liq-
3 uid-crystal light valve modulator — a subsystem very unlike
4 the spatial laser-beam modulation in the reading stage —
5 ordinarily there must indeed be focusing in the writing stage.

6 (ii) swept laser diodes — My invention does not
7 require a CRT. An alternative system directs the amplitude-
8 modulated image signals 233 (Fig. 16) in each channel to a
9 respective laser diode 232. The diode responds by emitting a
10 correspondingly amplitude-modulated laser-light beam.

11 This beam is processed in two-dimensional sweeping devi-
12 ces 264 (such as polygon mirrors, galvanometer mirrors etc.)
13 to yield a two-dimensionally scanning laser-light beam 231.
14 As before, the two-dimensional sweep 264 is synchronized 265
15 with the one-dimensional sweep 20 of the laser beam on the as-
16 sociated light valve.

17 This substitution of a laser-diode subsystem for a CRT
18 may benefit from the superior sharpness or definition of a
19 scanning laser spot. In any event my invention encompasses
20 use of such a subsystem.

21 All three laser-diode beams can be of the same color, and
22 this "color" if preferred can be infrared or ultraviolet rath-
23 er than visible. It is not necessary that they match the pro-
24 jection-beam colors, since these writing beams are only in the

1 optically isolated input stage of the light valve and there-
2 fore never seen by an audience. (The remainder of the optical
3 system is essentially the same as in Fig. 16.)

4 (iii) transmissive LCD modulators — As mentioned
5 earlier an LCD modulator (sometimes instead confusingly called
6 a "transmissive liquid-crystal valve modulator") is unsuited
7 for direct use in large-format projectors. This unsuitability
8 is due to conspicuousness of the electrode pattern when used
9 to form a greatly enlarged image; in addition, such a modula-
10 tor would not appear to be capable of infinite sharpness.

11 When substituted for a CRT or swept-laser-diode system in
12 the input writing stage of a liquid-crystal light valve, how-
13 ever, a transmissive LCD 332 (Fig. 17) should serve well. I
14 believe that the image of the electrode pattern can be pre-
15 vented from carrying through the liquid-crystal light valve to
16 appear conspicuously in the projected output image — particu-
17 larly with suitable choice of wavelength for excitation 366 of
18 the LCDs 332, relative to the absorption spectrum and partic-
19 ularly refractive-index spectrum of the electrode material.

20 Light from these sources 366 (preferably but not neces-
21 sarily laser diodes) passes through the LCDs, which meanwhile
22 are written electronically by image data 363 — with the hori-
23 zontal retrace synched 365 to the laser-beam sweep. Each LCD

1 output beam 331 proceeds into the writing stage of the corre-
2 sponding light valve.

3 (iv) direct electronic writing — All the foregoing
4 embodiments utilize optical writing to the liquid-crystal
5 light valve modulators. My invention, however, does not de-
6 pend upon optical writing.

7 Also within the scope of the invention and certain of the
8 appended claims is a system of writing image information 463
9 (Fig. 18) as an electronic signal, directly to an electronic
10 writing stage of a liquid-crystal light valve. It will be
11 understood by those skilled in the art that the light valve
12 now must be of a type which itself has an array of writing
13 electrodes rather than a photosensitive writing surface.

14 Since the electrodes are on the writing side of the
15 opaque dielectric mirror in the light valve, they cannot be
16 seen on the high-power laser writing-beam side of the valve.
17 As noted above, the two stages are optically isolated.

18 Those skilled in this field will recognize, by comparison
19 of Fig. 18 with Figs. 15 through 17, that this form of my in-
20 vention eliminates a CRT 32 and optical coupler 31 (Fig. 1)
21 from each color channel, without evident penalty. As in the
22 other systems discussed, vertical progression of the image-
23 data presentation 431 to the modulator is advantageously
24 synchronized with the laser-beam sweep.

1 (v) still film — Whereas the optical intermediary
2 stage (CRT and coupler) thus may be superfluous, on the other
3 hand for certain applications the same may be true of elec-
4 tronic intermediaries. A color slide or transparency 560
5 (Fig. 19), color print, or other color image medium may be
6 used as the color-image input — with no electronics whatso-
7 ever, upstream of the modulator writing stage.

8 Thus my invention may convert any very large outdoor area
9 into a lecture hall or travelogue theater, for presentation of
10 conventional slides or transparencies before a tremendous aud-
11 ience. A building, cliff or other reasonably vertical and
12 uniformly colored surface may serve as projection medium.

13 For a transparency, suitable illumination 566 is desired,
14 and a conventional optical train 562 for extracting primary-
15 color images 563, 531. Preferably these are conventionally
16 focused on photosensitive input stages of respective liquid-
17 crystal valves.

18 To maintain some, though not all, of the benefits of my
19 invention, one-dimensional sweep 520 should be provided. As
20 the primary images 573, 531 are not written incrementally,
21 however, this sweep need not be synchronized with anything.

22 (vi) motion-picture film — Essentially the same
23 system (Fig. 19) may be used to project greatly enlarged and
24 powerful laser-beam images from motion-picture film. The film

1 can be stepped through the image plane 560 using a generally
2 conventional film gate and sprocket system (not shown).

3 Although the modern trend is plainly toward digital re-
4 cording, storage and playback — which is to say elimination
5 of film as a medium for both new and legacy movies — yet
6 there remain many thousands of fine motion pictures in film
7 form. Projection from such originals directly, without intro-
8 duction of any pixel or raster structure into the viewed im-
9 age, may present a viewing experience having at least artistic
10 or antiquarian value.

11 Such a system can be used at very low light levels in the
12 writing stage, thus permitting excellent image quality in an
13 extremely large theater or outdoor-amphitheater without over-
14 heating the film. The system thereby avoids significant de-
15 terioration of — for example — a relatively old or otherwise
16 fragile movie print. In this case the amount of make-ready
17 for each motion picture is minimal in terms of both effort and
18 cost: the film is simply run through the writing stage of the
19 projector and viewed in brilliant, vivid color on the jumbo
20 screen.

21 Alternatively if desired color separations 660 (Fig. 20),
22 either positive or negative, can be made (or in some cases may
23 be available) in strip form from a motion-picture film print
24 or master. The construction and the conventional operating

1 mode of a liquid-crystal light valve ordinarily call for a
2 positive optical input image, but modification to operate from
3 a negative image would appear feasible.

4 Accordingly the three primary separations 660 may be
5 stepped through coordinated sprocket-and-gate mechanisms to
6 project independent image sequences 663, 631 onto the photo-
7 sensitive writing stages of liquid-crystal light valves. The
8 remainder of the projection system is as before. Due to the
9 need for mechanical synchronization, color registration in
10 this form of the invention may be more troublesome than that
11 in the single-print form (Fig. 19).

12 (vii) direct live image — Still another function
13 that need not necessarily be present in every embodiment of my
14 invention is image storage. Modernly many public events such
15 as large outdoor religious celebrations, political-convention
16 speakers, certain kinds of concerts, and even certain rela-
17 tively static sporting events (such as baseball games) are
18 popularly accompanied by projection of huge video images of
19 the celebrants, speakers, performers or players — in real
20 time.

21 Often the projected images appear directly above and
22 behind the people who are celebrating, performing etc. As is
23 well known, due to use of conventional video imaging the pic-

1 tures are typically of poor resolution, sharpness, contrast
2 and even brightness.

3 My invention can be used to project an extraordinarily
4 high-quality live image of such celebrants, speakers etc. 766
5 (Fig. 21) who are at a stage or podium. A conventional tele-
6 photo lens 701 is pointed toward the subject 766, to acquire
7 an image 760 in the usual way.

8 Rather than being directed to the photosensitive surface
9 of a video camera, however, the image 760 is redirected by
10 folding mirrors 702, 703 to a filter system 762 such as in the
11 Fig. 19 system — and thence in real time, and without any
12 sort of electronic intervention or image storage — to a pro-
13 jection system as described earlier. The same image, enor-
14 mously enlarged, is then returned to appear 746 on a giant
15 projection screen 747.

16 As to quality, it should be fully appreciated that in
17 this system there is no source whatsoever of any raster or
18 pixel structure. Rather the resolution and sharpness of the
19 displayed image 746 are limited only by the focal quality of
20 the lens 701 and the molecular processes in the two stages of
21 the liquid-crystal light valve modulators.

22 To ensure this condition, the illustrated beam-turning
23 system of folding mirrors (with a light-sealed tube enclosure)
24 will commonly be preferable to a fiber-optic light pipe, since

1 the latter may exhibit some visible granularity under the ex-
2 tremely high enlargement taken in the final projection stage.
3 A very fine-fiber light pipe, however, may serve.

4 In either case it may be desired to provide purely opti-
5 cal switching, fading and vignetting arrangements — as well
6 as mechanisms for pointing the lens 701 in different direc-
7 tions without losing either the image 766 or its orientation
8 or focus. Subsystems (not illustrated) of this sort enable
9 selection or combination of different real-time views in dif-
10 ferent directions from a single projector, for display on the
11 screen.

12
13 e) Speckle suppression — My invention incorporates sev-
14 eral distinct contributors to the inhibition of visible spec-
15 kle. These are discussed below.

16 (i) beam sweep — As previously mentioned the de-
17 flecting oscillatory mirrors 20 serve several distinct purpo-
18 ses. A particularly striking purpose is minimization of
19 speckle.

20 In the art this function has been addressed with a great
21 variety of devices, almost all of which tend to degrade the
22 brightness and collimation or pseudocollimation (as well as
23 the coherence) of the laser beam and thereby limit the quality
24 of the projected image or the economics of producing it, or

1 both. Earlier devices also add single-purpose equipment to
2 the projector, inevitably increasing cost, maintenance re-
3 quirements and simplicity of the finished product.

4 None of these objections applies to my invention, which
5 achieves a significant degree of speckle reduction using the
6 simple deflecting oscillating mirrors 20 that also serve sev-
7 eral other very beneficial purposes in the projector — there-
8 by achieving a desirable economy in manufacture and maintain-
9 ability. The mirrors are high-quality optical surfaces that
10 introduce no deterioration of the beam or image quality —
11 thereby achieving a further economy in optical energy.

12 The mirrors 20 sweep the downward-directed beams 22 back
13 and forth over the tops of the respective recollimators 23,
14 but always within the apertures of those lenses, and into the
15 entry faces 24 of polarizer-analyzer cubes 25. Each mirror
16 moves in response to electronic control signals — which may
17 be regarded as graphed at 20, Fig. 22 — directed to the cor-
18 responding mirror driver 21.

19 Ideally, however, the control signals may be varied in
20 such a way that the illustrated straight ramp 20 represents a
21 constant rate of positional scan of the beam along each entry
22 face 24 (and therefore along the modulator face and the pro-
23 jection medium). This is theoretically preferable to a con-
24 stant rate of signal change or a constant change of angle.

1 Nevertheless in practice the angle through which the beam
2 sweeps over the recollimators 23, in view of the length of
3 travel between the oscillating mirrors 20 and recollimators,
4 is small enough that ordinarily the scan speed is adequately
5 constant in positional terms.

6 Operation of each mirror 20 is advantageously controlled
7 in correspondence with incremental writing of the image signal
8 31 to the CRT 32 — or to a liquid-crystal light valve elec-
9 trode, laser diode, or other writing system such as enumerated
10 in the preceding subsection "d". Naturally this condition is
11 inapplicable to full-frame or nonincremental writing systems
12 (Figs. 19-21).

13 Incremental writing, where used, may typically be charac-
14 terized by raster pixel and line advance states or signals 64
15 (Fig. 22), with a vertical blanking interval 67. It is known
16 that the writing processes of a liquid-crystal light valve
17 have a certain very short lag time, commonly on the order of a
18 small number of pixel periods — and also a persistence
19 period, typically corresponding to the time in which a few
20 raster lines are written.

21 Preferably the mirror sweep signal 20 (Fig. 22) is ini-
22 tially delayed by a time 68 (at left end of the drawing) re-
23 lated to the writing-process delay. Mechanical flyback 69 of

1 the mirror may be effected during a like interval 68 (right
2 end of the drawing) .

3 The precise mechanism by which the mirror sweep suppres-
4 ses speckle is not absolutely clear; however, the resulting
5 suppression is a fact, and the validity of my invention is not
6 to be deemed dependent upon a reliable explanation. The most
7 plausible explanation of which I am aware relates primarily to
8 shifts, and perhaps to a lesser extent disruption, of coher-
9 ence — through changes in the pathlength to each point on the
10 projection medium, as the down beam 22 scans over the central
11 layer 26 of each cube 25.

12 That beam scans leftward and downward along the interface
13 layer 26, not entirely by displacement but in part by changing
14 incidence angle — on account of the rotation of mirror 20,
15 120 or the optical rotation within the cell 61. As an exam-
16 ple, incoming rays 22p-22w (Fig. 23) which in one instant are
17 near vertical will be redirected, only a very small fraction
18 of a second later, as inclined rays 22p'-22w' (Fig. 24) at a
19 small angle off (to the left of) vertical. The inclined rays
20 reach the interface 26 slightly to the left of their previous
21 positions when vertical.

22 (For clarity of the illustrations the angular offset from
23 vertical may be exaggerated. Also the reading-beam rays di-
24 rected from the interface 26 toward the liquid-crystal light

1 valve are all drawn at slight angles to the horizontal, as
2 they approach the mirror 30' that separates the writing stage,
3 at left, from the reading stage in the liquid-crystal light
4 valve 30. Similarly the rays returned from that mirror to the
5 cube interface are all drawn at opposing slight angles to the
6 horizontal, so that the actually horizontal return rays 34p"-
7 34v" can be distinguished from the also-horizontal inbound
8 rays 22p-22v. In these very simplified drawings the recolli-
9 mator 23 and cube faces 24, 27 have been omitted, so that ac-
10 tually-angled rays to the recollimator are represented more
11 simply as angled rays to the interface 26 — whereas actually
12 the rays reaching the interface 26 have been recollimated and
13 are nearly vertical for all beam positions. It will be
14 realized by those skilled in the art that these simplifica-
15 tions are immaterial to the following analysis.)

16 As the reading beam shifts downward along the modulator
17 mirror, passing writing-stage rays 32p-32v that represent a
18 particular group of image points or lines, the initial corre-
19 spondence between reading-beam rays 22p-22v and writing-stage
20 rays 32p-32v is lost. Thus for instance a particular upper
21 writing ray 32v that initially controls a particular ray 22v,
22 22v" (Fig. 23) in the near-vertical reading beam, later
23 controls a shifted ray 22w' (Fig. 24) which is to the right
24 (and lower) in the displaced, angled reading beam.

1 Likewise lower writing rays 32q-32u respectively control
2 certain reading-beam rays 22q-22u, 22q''-22u'' (Fig. 23) in the
3 vertical beam, and instead control shifted reading-beam rays
4 22s'-22v' (Fig. 24) in the displaced, angled reading beam. In
5 particular some reading-beam rays 22p that initially partici-
6 pate in the imaging of the writing-beam rays 32p will — in
7 another instant — pass beyond these particular writing rays.
8 Thus a corresponding angled ray 22p' (Fig. 24) moves below the
9 illustrated writing-beam region.

10 In most positions such an angled ray can be used for
11 imaging of part of a later-written raster line (not shown).
12 Conversely a reading-beam ray 22w that initially is too high
13 to participate in imaging the particular writing-beam rays
14 illustrated, will later shift into position 22w' for imaging
15 the topmost reading-beam ray 32v.

16 Now with these geometrical relations in mind it can be
17 recognized that the horizontal return beam paths from the mod-
18 ulator mirror to the cube interface 26 are shorter for the
19 angled, leftward-displaced beam (Fig. 24) than for the initial
20 vertical beam (Fig. 23). The paths from that mirror to the
21 projection screen are, at least in comparison with the other
22 relationships discussed here, substantially unchanged.

23 On the other hand the down-beam paths from the oscillat-
24 ing mirror to the cube interface 26 are longer for the left-

ward beam (Fig. 24) than for the initial beam (Fig. 23). Given a forty-five degree angle at the interface 26, the increase in vertical travel should just cancel the decrease in horizontal travel; however, this is not quite the end of the story.

There are several second-order effects. First, in addition to being displaced, the later beam is also differently angled. The distance traveled along the hypotenuse of the beam path is clearly longer for a more steeply angled beam (Fig. 24) than a more nearly vertical one (Fig. 23).

Hence for each writing ray 32p-32v, the reading-beam pathlength used for expressing that ray at the projection medium 47 changes continuously. For instance the very same writing ray 32s has at one instant a relatively shorter distance to the screen, due to the near-vertical beam path 22p (Fig. 23) — and at the next instant a longer distance to the screen by virtue of the extended hypotenuse along the angled path 22p' (Fig. 24). Although the differences are small by commonplace standards of comparison, they are extremely large in relation to the wavelength of light.

Still more interestingly, the earlier-discussed beam expansion, introduced by the negative lens 18, causes this difference in hypotenuse lengths to vary from ray 22p to ray 22q, etc., within the beam. Although no attempt has been made to represent this more-subtle effect in the drawings, those

1 skilled in the art will understand that each ray 22p, 22q
2 . . . 22v, as it propagates downward, is angled leftward
3 (i. e. clockwise) relative to all the rays 22q, 22s . . . 22w
4 which are to its right in the beam.

5 This differential angling due to the beam expansion in-
6 teracts with the progressive difference in hypotenuse lengths,
7 making the size of the difference itself vary as the process
8 continues. The precise behavior of the system may depend upon
9 the particular contours of brightness-trim optics used at the
10 width-expanding lens 19 or curved mirror 120. For the simpler
11 case of a cylindrical lens 19 and planar mirror 20, the
12 variation may be in the nature of a continuing acceleration of
13 the pathlength difference from moment to moment, as the ray
14 angle steepens ever more quickly with rotation of the mirror.

15 Whether acceleration or deceleration, or a more-complex
16 behavior, the effect on beam coherence is not only a shift in
17 absolute terms, i. e. in terms of the time for an image ray to
18 reach the screen, but also a perturbation differentially —
19 which amounts to a disruption. In effect the planar wave-
20 fronts of the beam acquire a cylindrical (but probably not a
21 circular-cylindrical) twist.

22 This geometry is still further complicated by similar
23 relations that could be examined at the oscillating mirror 20
24 or in the cell 61 — and which in some situations may tend to

1 compensate for the pathlength differences described above.

2 Due to the smaller transverse dimensions of the beam in the
3 upper tier, however, those variations cannot overcome the
4 larger dimensional changes described.

5 (As suggested earlier, simplifications in the drawings
6 and corresponding discussion — for the sake of clarity —
7 cause the hypotenuse paths to be defined in relation to the
8 cube interface 26. In actuality the angled-path phenomena are
9 primarily with respect to interception of beams at the recol-
10 limator 23, not really at the interface 26. It can now be
11 seen, however, that the principles described have not been
12 significantly misrepresented in this simplified presentation.
13 Although I have referred to the near-vertical beam condition
14 of Fig. 23 as the initial condition, it is only "initial" for
15 purposes of comparison between Figs. 23 and Fig. 24; more gen-
16 erally if desired the beam may be made to sweep from a first
17 condition per Fig. 5 in which the beam is angled rightward
18 from vertical, as it propagates downward, through a vertical
19 condition in Figs. 23 and 6, and finally to the oppositely
20 angled condition of Figs. 24 and 7. Thus some of the differ-
21 ential angle effects discussed above may, in some portions of
22 the beam sweep, have opposite polarity than those indicated in
23 the discussion.)

1 For each position of the beam as described above, speckle
2 is theoretically present — but the speckle pattern for each
3 position of the beam is significantly different from that for
4 every other position. Speckle patterns are understood to
5 arise in the eye due to interferences from neighboring screen
6 positions that are separated by distances only on the order of
7 a wavelength of light. Even tiny changes in projection path-
8 length, changes on the order of the wavelength, therefore can
9 significantly shift or totally change the speckle pattern.

10 As the beam sweeps swiftly along the central layer 26,
11 the speckle pattern therefore moves, and also changes, very
12 quickly — far more rapidly than the eye and brain can follow
13 it. The human vision mechanisms tend to average out the dif-
14 ferences among the myriad diverse speckle patterns as they
15 flash by, strongly decreasing the viewer's ability to distin-
16 guish or to perceive any single one pattern or category of
17 patterns.

18 While thus greatly reducing or in many cases even elimi-
19 nating visible speckle, my invention as described to this
20 point avoids all the diffusers, absorbers and like unproduc-
21 tive encumbrances proposed in the prior art. This speckle-
22 reduction feature of my invention accordingly promotes economy
23 both of manufacture and of optical energy.

1 (ii) light-valve spatial modulation — It has been
2 my observation, however, that under certain experimental cir-
3 cumstances a small residual of speckle may be perceived. I
4 have discovered that, remarkably, use of the liquid-crystal
5 light valve itself is helpful in removing this residual.

6 Although I have disproved the theory that such a valve —
7 because it degrades beam coherence — must fail to produce in-
8 finite sharpness, nevertheless the degradation of beam coher-
9 ence in the valve is significant. It may be that degradation
10 which is responsible for the observed role of the valve in
11 further suppressing residual speckle.

12 The reason for this seems to be that some neighboring re-
13 gions of an image — where coherent laser light could inter-
14 fere at the eye, to produce speckle — are prevented from
15 doing so by slight phase shifts as between those neighboring
16 regions. These phase shifts are associated with the produc-
17 tion of a latent image in polarization, as described earlier.

18 Thus for example consider first a region of the liquid-
19 crystal modulator where the writing beam is dark, or in other
20 words where the writing ray 32v (shown in the broken line) has
21 null intensity. Next consider the returned reading-beam ray
22 34v, propagating from the valve mirror toward the entry
23 surface of the valve — still at the position of that null
24 writing ray 32v.

1 Suppose now that for a null-brightness condition 32v the
2 calibration or adjustment of the valve brings some particular
3 wavefront 72v in that returned reading beam just exactly back
4 to the entry surface of the valve at a certain instant in
5 time. For purposes of simplicity we assume that a correspond-
6 ing wavefront 73v (also in the broken line) in the projection
7 ray 38v-45v just reaches the projection screen at that same
8 instant. Since this ray too, like the corresponding writing
9 ray 32v, should be null, the wavefront 73v is something of an
10 abstraction but will serve as an important reference in this
11 discussion.

12 An adjacent writing ray 32u (drawn with a lightweight
13 line) we assume is instead very dim but not of zero energy,
14 and — through the modulation processes of the valve — delays
15 the corresponding return ray 34u (also in lightweight line) so
16 that a portion 72u' of the same wavefront 72v' cannot quite
17 reach the valve entry surface, at the above-defined "certain
18 instant". The wavefront portion 72u' is thus second to the
19 null portion 72v' (but only by a nose), and roughly this same
20 very small retardation will be preserved at the projection
21 screen 47 for a portion 73u' of the same wavefront as the null
22 wavefront 73v at the screen.

23 The retardation in terms of physical distance will be
24 slightly greater, making allowance for the difference in

1 propagation speeds through the remainder of the modulator and
2 through the air between cube and screen. (As will be under-
3 stood, this retardation is shown greatly exaggerated in com-
4 parison with the schematically illustrated distance from the
5 cube to the screen.)

6 Analogously a very bright writing ray 32s (drawn with a
7 bold line) will much more strongly delay its reading ray 34s,
8 so that its corresponding fraction 72s of the initially common
9 wavefront 72v-72u may perhaps only be able to just leave the
10 mirror before the "certain instant". Before making its way
11 out of the optically dense materials of the modulator and
12 cube, the reading ray 34s (also drawn bold) will give up an
13 even greater handicap to the null and dim rays 34v, 34u, which
14 by then will have moved ahead much more quickly through the
15 air toward the screen. Accordingly the retardation of the
16 forward wavefront 73s, in terms of distance at the screen,
17 will be accentuated.

18 Also assumed for purposes of explanation are two additio-
19 nal writing rays 32q, 32p which both have brightness (as well
20 as line weight in the diagram) that is intermediate between
21 those of the rays 32u, 32s just considered. For these two
22 rays a likewise intermediate amount of delay will bring their
23 corresponding portions 72q, 72p of the above-discussed common
24 wavefront to an intermediate position within the modulator.

1 As before, this delay — somewhat amplified by the difference
2 in densities of the modulator and cube vs. air, will also
3 appear for the corresponding forward wavefront segments 73q,
4 73p near the screen.

5 Now it can be seen from inspection of the several wave-
6 front-fragment representations 73p-73v near the screen 47 that
7 coherence, and therefore capability to sustain speckle, is
8 strongly fragmented by the light valve. This particular bene-
9 ficial effect, however, is available only in portions of the
10 image having spatially abrupt variations in brightness for
11 closely adjacent writing rays 32p-32v — and not for portions
12 of uniform brightness.

13 The effect just discussed for the equal-brightness writ-
14 ing rays 32q, 32p also interacts with the previously discussed
15 beam-angle effect, and furthermore with the differential angle
16 effect — both discussed in the preceding subsection "ii".
17 Such interaction can introduce differential delays between the
18 reading-beam rays 38p'-45p', 38q'-45q' resulting from such
19 equal-brightness writing rays 32p, 32q.

20 This effect is suggested in schematic showings of the
21 corresponding wavefront portions 72q', 72p' (Fig. 24) within
22 the modulator — and downstream wavefront portions 73q', 73p'
23 — thus further fragmenting beam coherence even in areas of
24 uniform image brightness.

1 (iii) wavelength mixture — Still further helpful
2 in speckle suppression is the introduction of cyan light in
3 conjunction with the long-wavelength (over 635 nm, and prefer-
4 ably between 635 and 650 nm; most preferably 647 nm) primary
5 red light. As suggested previously this enhancement may be
6 due to a kind of admixture or dilution by wavelengths that are
7 present in relatively pure form but cannot constructively or
8 destructively interfere with the primaries.

9 It is also possible that those wavelengths themselves in-
10 troduce some amount of another speckle component that helps to
11 perceptually mask the speckle due to the primaries. In any
12 event, this additional refinement in speckle suppression may
13 be particularly helpful in, for example, portions of an image
14 that are uniform in color and brightness — so that the light
15 valve cannot provide effective disruption of coherence.

16 (iv) projection surface — In practice of my inven-
17 tion I have further found that a high-gain projection screen
18 should be avoided to yet further minimize speckle. A conven-
19 tion low-gain screen is preferable. For shows in environments
20 not requiring highest image intensity, an even more low-key
21 projection medium such as a fine cloth screen may facilitate
22 best speckle control, as well as imparting the most natural
23 appearance to earth and skin tones.
24

1 f) Beam artifact control, and energy efficiency — My
2 invention enjoys easily, for the first time in a laser projec-
3 tor, the advantages which were proposed by Henderson, Schmidt
4 and Gold but so elusive in the context of an incandescent
5 (e. g. arc) lamp. One such benefit that is particularly
6 important involves masking losses.

7 (i) laser-beam intensity profiles — Possibly one
8 obstacle in the arc-lamp environment arose from a Gaussian
9 distribution in the shallow slot-shaped beam, as asserted by
10 Henderson. The basis of that assertion is not clear to me,
11 but in any event one of the most common sorts of laser beams
12 — known as a "TM00 transverse mode" (Fig. 25) — has a like
13 distribution.

14 By comparison an ideal intensity distribution across an
15 illumination beam for use in a liquid-crystal light valve
16 would be uniform — familiarly called a "tophat" distribution
17 TH, for its resemblance to a very old-fashioned formal top
18 hat. The departure of a TM00 beam from such a tophat dis-
19 tribution, as the illustration shows, implies that the beam
20 periphery is relatively dark, or dim, in comparison with a
21 bright region tailing off in all directions from the center.

22 The cross-sectional distributions illustrated are not
23 merely one-dimensional — as for example from left to right
24 across an image, or from top to bottom — but rather two-di-

1 mensional and with circular symmetry about the centerline ξ .
2 Therefore it is the entire circumference, the annular region
3 near the overall beam or aperture radius $\pm r$ in the drawing,
4 which is degraded. Particularly for square or rectangular
5 images, as will shortly be seen, such a two-dimensional effect
6 becomes difficult to correct or compensate.

7 Another common type of laser beam is a so-called "TM00
8 transverse mode". As shown, this sort of beam considerably
9 better equalizes the intensity distribution at the center with
10 respect to the intermediate regions that are, say, halfway out
11 from the center to the beam edge. An intensity minimum ap-
12 pears at the center which (for reasons that will become clear
13 momentarily) does not create a significant problem and in fact
14 may be advantageous.

15 The lower brightness about the periphery, however, is
16 still a severe obstacle to uniform illumination in a final
17 projected image. Thus at the outset some laser beams have
18 brightness-distribution characteristics that limit ultimate
19 performance and may be comparable to those mentioned.

20 A new dimension is introduced, however, by certain kinds
21 of multimode laser beams (Fig. 25a, and the uppermost section
22 of Fig. 29). No attempt is made in this document to represent
23 the intensity function across such a beam accurately; the re-
24 lationships are illustrated only very conceptually.

1 As shown, the brightness cross-section commonly has a
2 central declivity C analogous to that in the TM₀₁ beam, and an
3 intermediate region of brightness ripples R which an engineer
4 or scientist might describe as "ringing down". The brightness
5 distribution also exhibits a peripheral edge or limb L that
6 falls very abruptly — just immediately inside the beam aper-
7 ture — to a minimum that is essentially zero at the edge \underline{r} .

8 Multimode beams as such were not invented by me, and are
9 well known; however, they are a particularly valuable refine-
10 ment of my invention. They provide a very acceptable approxi-
11 mation to the ideal tophat function TH mentioned earlier. All
12 the fluctuations within the main body of the beam, i. e. in-
13 side the limb L, are relatively quite small as a fraction of
14 the maximum brightness.

15 (ii) visible beam nonuniformities — Nevertheless
16 these fluctuations and others are plainly visible and in fact
17 very conspicuous if a laser beam is merely enlarged and stat-
18 ically projected onto a viewing surface, in a liquid-crystal
19 light-valve system. The mode-related intensity variation ap-
20 pears as a series of bright annular zones, with annular maxima
21 of brightness represented very roughly by the inner concentric
22 circles within the aperture radius \underline{r} (top view of Fig. 29).

23 In my opinion, showing a motion picture or other natural-
24 scene image by simply modulating such a beam with the image,

1 and projecting the modulated beam onto a screen, would be a
2 total failure. The worst of it, however, has yet to be poin-
3 ted out.

4 In addition to the geometrically regular variations, a
5 laser beam projected via a liquid-crystal light valve is sub-
6 ject to myriad erratic but strongly defined artifacts A (Fig.
7 29). It has been suggested to me that these features arise
8 from the polarization- and phase-based character of the light
9 valve, as used with near-monochromatic laser radiation.

10 Closely analogous optical trains are used for the specif-
11 ic purpose of displaying in stark, high-contrast relief cer-
12 tain extremely subtle optical effects. One such device, for
13 example, is the phase-contrast microscope, for which Fritz
14 Zernike received the 1953 Nobel Prize. It converts wispy,
15 indistinct images of ultrathin biological specimens to well-
16 defined and much more easily studied pictures.

17 This advantage, in phase microscopes and phase-based
18 quality-control systems, becomes very much the opposite when
19 it is manifested in the sensitivity of a liquid-crystal and
20 laser projector to minor defects or even subtle stress pat-
21 terns within the optics of a near-monochromatic laser projec-
22 tor channel. (Such phenomena undoubtedly occur in an arc-
23 based system — as for example in a Hughes projector — but

1 probably are averaged out by the variations due to the broad
2 spectrum in each primary-color beam.)

3 As shown, some of the resulting artifacts appear to be
4 well-defined oval shapes, often having a linear outline, while
5 others have the appearance of irregular and sometimes moving
6 or floating pieces of trash. All these features would be
7 extremely distracting and contrary to desired esthetics of a
8 projected motion picture or other image. Thus an important
9 part of the successful practice of my invention consists of
10 managing these artifacts.

11 (iii) the masking problem — Another important
12 part, mentioned earlier, is in avoiding energy losses that
13 arise through ordinary beam masking. The beam-masking problem
14 can be analyzed quantitatively through simple geometry and
15 arithmetic. Customarily a laser beam, like the white light
16 beam in an arc-based system, is originally circular — al-
17 though the reasons for this similarity are different.

18 If such a beam is used directly to project a square image
19 774 (Fig. 26), naturally to avoid totally dark corners the
20 square projection beam must be extracted from the circular
21 original beam in such a way that the square corners of the
22 projection beam are entirely within the bright area of the
23 original circular beam. On the other hand, minimum light

1 should be wasted, so the square corners should not be spaced
2 far inward from the circular beam edge.

3 (Starting with Fig. 26, and in Fig. 29 the second view,
4 the outer circle in the drawings may be regarded as slightly
5 redefined. No longer does it represent the initial laser
6 aperture \pm_r of Figs. 25, 25a but rather the effective aperture
7 physically defined by the sharply cut-off peripheral limb L.)

8 The best that can be done, the ideal, is to inscribe the
9 square within the circle as illustrated. In this relationship
10 the diagonal of the square equals the diameter of the circle.
11 If we call that common distance \underline{d} , then the area of the square
12 is $\underline{d}^2/2$ and the area of the circle is $\pi \underline{d}^2/4$.

13 Now the fraction of the circular beam that is employed in
14 forming the square beam is the ratio of these two expressions,
15 which is $2/\pi$ or 0.64; therefore the fraction that is discar-
16 ded is $1 - 0.64 = 0.36$ or thirty-six percent. More than a
17 third of the optical energy in the laser beam would be just
18 thrown away.

19 Commercial motion pictures and most natural-scene photog-
20 raphy, however, nowadays seldom use a square format. One
21 more-highly preferred format is 3:4 (Fig. 27). To determine
22 the amount of laser energy that is wasted, again we assume
23 that the format (now rectangular) is inscribed within the
24 circular source beam and calculate the two areas.

1 In this case convenient dimensional units are sides of
2 the three vertical and four horizontal square internal cells,
3 so that a diagonal \underline{d} is given by $\underline{d}^2 = 3^2 + 4^2 = 5^2$, and $\underline{d} = 5$.
4 Now the area of the rectangle is $3 \times 4 = 12$, and the area of
5 the circle is $\pi \underline{d}^2 / 4 = 5^2 \pi / 4 = 6\frac{1}{4}\pi$. Here the fraction used is
6 the ratio of 12 to $6\frac{1}{4}\pi$, namely 0.61, so the discarded frac-
7 tion is $1 - 0.61 = 0.39$ or thirty-nine percent, slightly worse
8 than the square-format case.

9 For wide-screen shows, the format preferred is 9:16 (Fig.
10 28), where the diagonal \underline{d} can be found from $\underline{d}^2 = 9^2 + 16^2 =$
11 337, and $\underline{d} = 18.4$. Here the area of the rectangle is $9 \times 16 =$
12 144, and the area of the circle again $\pi \underline{d}^2 / 4 = 337\pi / 4 = 84\frac{1}{4}\pi$,
13 for a used-energy fraction of $144 / 84\frac{1}{4}\pi = 0.54$, only just over
14 half. Forty-six percent, nearly half, is discarded.

15 (iv) a unitary solution — Preferred embodiments of
16 my invention resolve both the management of artifacts and this
17 energy-efficiency problem, and do so by a single, simple sys-
18 tem that also effectuates the speckle suppression discussed in
19 foregoing subsection "e". Specifically, as previously de-
20 scribed the optics 18, 19 (Figs. 5, 8 and 9) may in effect
21 simply collapse the initially circular laser beam 11 (Fig. 29)
22 to a shallow oval or elliptical beam 22; and the very small
23 amount of energy in the extreme wings 75 is then masked off at

1 tm as illustrated, before the sweeping of the beam down the
2 projection medium.

3 Although the beam is thus changed in shape, the original
4 energy distribution in the beam — i. e., the not-quite-uniform
5 pattern of annular brightness rings (top view in Fig. 29)
6 — when collapsed to a function along a diametral cross-section,
7 will generally approximate a semicircular function 76
8 (Fig. 29). If the original circular beam were entirely uniform,
9 the pattern would be semicircular, necessarily remaining
10 unchanged from the circular shape of the original beam.

11 Here the several circular brightness ripples R tend to
12 partially wash out one another, the upper and lower arches of
13 the ringlike brightness patterns compensating in part for the
14 dimmer center. As a result, the only pattern of fluctuations
15 that remains, superimposed on the semicircular distribution
16 76, is considerably better neutralized or homogenized.

17 Furthermore all the highly localized trash due to dust
18 specks — or microscopic stress points, dimples or bubbles in
19 optical glass — and other artifacts A are greatly diluted in
20 the brightness of the rest of the beam, and are in effect
21 washed out. The overall distribution 76 is now much smoother
22 and easier to use for projection purposes.

23 (v) one-dimensional compensation — To provide a
24 reasonably constant or uniform energy distribution along this

1 flattened beam, some compensating function 77 is required.

2 This correcting function is essentially a circular chordal
3 shape, not quite a complete semicircle, in view of the masking
4 near the ends.

5 Although this compensation may seem to be a very signifi-
6 cant additional step, it is only necessary along an essential-
7 ly linear or one-dimensional region — not within a two-dimen-
8 sional frame as discussed above with respect to Fig. 26. In
9 the process of collapsing the circular beam to a slot, all of
10 the artifacts A and ripples R are greatly smoothed out and
11 blended so that the one-dimensional compensation function is
12 the main adjustment that remains to be accomplished.

13 As suggested earlier, a preferable approach uses special
14 refractive elements for the initial entry optics 18, 19 — or
15 still more preferably a compound-curve molded mirror 120 (Fig.
16 10) — that may be customized to equalize both the energy dis-
17 tribution and the shape of the oval 22. With this approach,
18 after masking off the wings 275 one can achieve a more nearly
19 rectangular beam 222 with a very nearly flat distribution 276,
20 calling for at most very minor compensation 277 — all as
21 shown in the fourth view of Fig. 29.

22 These approaches are desirable to avoid the need for an
23 entirely separate optical compensator to impart the function

1 77 in the central view. (Furthermore they are helpful for
2 enhancing the functions discussed in subsection "g" below.)

3 (vi) sweep refinements — With the intensity dis-
4 tribution along the wide, shallow beam now smooth and substan-
5 tially uniform, to obtain a similarly uniform full frame for
6 image projection it remains only to sweep the beam vertically
7 over the screen. As shown in subsection "e" above, this is
8 accomplished in operation of the speckle-suppressing deflec-
9 tion system 18-20 that precedes the liquid-crystal light valve
10 modulators.

11 In consequence, considering here only the improvement
12 attained specifically through elimination of circular-to-rec-
13 tangular masking, the percentage increase in optical energy
14 used to form the image can be found from the three percentages
15 calculated above in subsection f(iii). For the three cases of
16 square, 4:3 and 16:9 screen aspect ratios, again those per-
17 centages are 36%, 39% and 46%.

18 For these same three cases, the improvements obtained
19 through avoidance of masking are by factors approaching
20 respectively $1/0.36 = 1.56$, $1/0.39 = 1.64$, and $1/0.46 = 1.85$.
21 In other words, the increases respectively approach 56%, 64%
22 and 85%. (Use of the word "approach" can now be more specif-
23 ically appreciated in terms of the very small amount of energy

1 lost at the right and left ends or wings 75, 275 of the shal-
2 low beam, between the full radius $\pm r$ and the mask $\pm m$.)

3 If desired, as suggested in subsection "e(i)", an addi-
4 tional refinement can be included without significant cost:
5 forcing the beam to scan at a substantially constant rate in
6 terms of distance down the modulator, rather than in terms of
7 the angle of the vibrating mirror or other deflector. Scan-
8 ning at a constant rate along the modulator should track the
9 writing beam at the input of the modulator more accurately.
10 This improvement, however, will be significant only if the
11 half angle of the beam sweep (recollimator radius divided by
12 distance from vibrating mirror to recollimator) is large
13 enough to introduce a tracking error greater than one or two
14 raster lines.

15 In such a case, the skilled person will understand that
16 for these purposes the rectilinear ramp 20 (Fig. 22) prefera-
17 bly represents position within the modulator height FF, rather
18 than galvanometer drive signal as such. The difference can be
19 understood simply from the geometry as a faster sweep along
20 the modulator for each angular increment when the beam is
21 already at a steep upward or downward angle than when it is
22 directed toward the central height of the frame.

23 In trigonometric terms, more specifically, the vertical
24 position is roughly proportional to the sine of the beam an-

1 gle; therefore the scan rate on the modulator can be equalized
2 by driving the galvanometer or other deflector with its in-
3 verse function, namely an arcsine-function signal. When the
4 angle changes as the arcsine of a constantly changing value
5 kt , commonly written " $\sin^{-1}(kt)$ ", screen position should vary
6 approximately as $\sin\{\sin^{-1}(kt)\} = kt$, or in other words at a
7 constant speed down the modulator frame.

8 If the projection throw (distance to the screen) is quite
9 short and the screen quite tall (or wide), a potential diffi-
10 culty may arise in distortion and nonuniform illumination of
11 the image due to the resulting relatively steep projection
12 angle. In conventional projection systems the focusing of the
13 beam on the screen by a field-curvature-correcting lens avoids
14 these effects.

15 As an example, consider image distortion — and variation
16 of image brightness — at the top or bottom of the screen with
17 respect to the center. At the extreme positions of sweep, the
18 distance to the screen is slightly greater, tending to spread
19 the constant-angular-height beam over a greater distance —
20 the beam cross-section varying with the reciprocal of the co-
21 sine of the off-axis angle of the beam relative to the system
22 centerline. The beam therefore suffers a decrease in apparent
23 brightness in each unit area, the brightness being proportio-
24 nal to the cosine.

1 Furthermore at its top or bottom the screen is more
2 strongly angled to the beam, tending to spread the beam even
3 further on the screen. This effect introduces another factor
4 of the reciprocal of the cosine in beam height along the
5 screen. Considering the two effects together, the screen
6 brightness must be proportional to the square of the cosine of
7 the off-axis angle.

8 To make the cosine-squared equal to, say, ninety percent
9 or more — and thereby to make the distortion and the bright-
10 ness-nonuniformity effect probably negligible — it is only
11 necessary to restrain the vertical half-angle at the screen to
12 no more than about thirty-two degrees. For a screen about
13 thirteen meters (forty feet) tall, this condition requires
14 that the projector be at least about 20 meters (roughly 60
15 feet) from the screen.

16 This is the easiest and most economical resolution, if
17 space allows. Otherwise it should be possible to employ, or
18 design by conventional techniques and then employ, a projec-
19 tion lens that corrects this factor.

20 In principle, like considerations may apply to horizontal
21 deformation and brightness uniformity near the right and left
22 ends of the screen. Equalization of brightness, however, if
23 problematic is controllable through the compensation 77 or 277
24 discussed earlier.

1 g) Contrast enhancement and image brightness — Here
2 too, my invention achieves easily, for the first time in a la-
3 ser projector, the advantages proposed by Henderson, Schmidt
4 and Gold but evidently not commerciable using arc sources.
5 This is accomplished by the same mechanisms used above to sup-
6 press speckle, conceal laser-beam artifacts, and minimize
7 masking losses.

8 (i) persistence zone — As mentioned earlier, op-
9 tical energy is wasted if the reading beam illuminates por-
10 tions of a liquid-crystal light valve where no image writing
11 is taking place (or has recently taken place) in the image-
12 input stage of the valve. Due to persistence effects in the
13 valve, reading light can still be returned through an analyzer
14 cube of my invention — and projected to a viewing screen —
15 if that light reaches a raster line within a short time after
16 that line has been written.

17 For any of the conventional or standard raster timings of
18 which I am aware, that short time typically amounts to the
19 time required to write a few raster lines. Such a slot-shaped
20 region, which is in effect a persistence zone, is very similar
21 in shape to the vertically collapsed beam 22, 222 (Fig. 29).

22 The persistence zone thus amounts to a fraction of the
23 full image height. That fraction is generally between one

1 tenth and perhaps one fifth or (with more margin for error)
2 one quarter.

3 (ii) synchronization and brightness — Flooding the
4 entire modulator frame therefore wastes three-quarters to
5 nine-tenths of the light energy by illuminating outside the
6 persistence zone. In other words, the image can be between
7 four and ten times brighter if the reading beam closely
8 conforms to the persistence zone. This implies that the
9 reading beam must be moved with the writing signal, as has in
10 fact been described for my invention, in earlier sections of
11 this document.

12 (iii) synchronization and contrast — Such syn-
13 chronization has an additional benefit. Although light wasted
14 in parts of the modulator outside the persistence zone cannot
15 produce any portion of an image, such light can degrade the
16 image. To the extent that the analyzer cube may leak light
17 that is not in the nominally selected polarization state, an
18 overall cast or very dimly lit background appears even in
19 areas that should be dead black.

20 Stray light may also arise from polarization imperfec-
21 tions in the source laser beam (although these should be re-
22 moved upon initial entry through the cube), or from spurious
23 polarization-degrading characteristics of the modulator it-
24 self. In any event, confining illumination to just a very

1 small envelope about the persistence zone reduces the overall
2 stray-light background by a factor of perhaps twenty — while
3 simultaneously raising image brightness by a factor of four to
4 ten as stated above.

5 Therefore this system in principle directly enhances the
6 inherently high contrast of the light-valve/cube system by a
7 multiple equal to the product of these numbers. Contrast is
8 thereby improved, at least theoretically, by a factor between
9 very roughly eighty and two hundred. (In practice it appears
10 that other considerations come into play to limit the contrast
11 improvement to factors well under eighty.)

12
13 h) Irregular projection media, infinite sharpness, and
14 projection distance — Acoustooptic modulators (AOMs) have
15 some capability for infinite sharpness and therefore for pro-
16 jection of images onto projection media at highly different
17 distances from the projector. This characteristic, however,
18 is essentially moot since AOMs are so poor in optical-energy
19 efficiency that it would be impractical to use them commer-
20 cially for any long-throw performance.

21 Liquid-crystal "displays" or "devices" are not able to
22 provide infinite sharpness. Projectors based on such devices
23 accordingly are limited to forming an image on a simple screen
24 in a conventional way.

1 Most other laser applications involve either focusing the
2 laser beam to a fine spot or projecting the beam unmodified.
3 In effect the laser is manipulated and viewed from outside the
4 beam, treated as if it were a tool or other object.

5 My invention is thus the first to effectively open up a
6 laser beam and manipulate it from the inside in such a way as
7 to provide both (1) infinite sharpness and (2) a beam that is
8 bright enough to effectively exploit that sharpness in a long-
9 throw environment.

10 It is known that the capability of a laser beam or any
11 other light beam to maintain its overall envelope and the in-
12 tegrity of its individual rays without intermixing or cross-
13 talk is fundamentally limited by diffraction. Scientists
14 speak of the "near field" of a laser beam, which describes the
15 behavior of the beam just outside the originating aperture
16 where the beam maintains a cylindrical envelope, and the "far
17 field" where the beam expands in a conical envelope.

18 In the near field, not only is the external shape con-
19 stant but also the intermixing or confusion of rays within the
20 beam is minimized. In the far field, both the external and
21 internal behavior degrade.

22 These phenomena are special cases of diffractive effects.
23 It is known that the distance to a region of transition be-
24 tween the near field and the far field is governed by the

1 relationships between the wavelength λ of the light and the
2 diameter \underline{d} of an aperture from which the light beam issues,
3 and more specifically the distance to the transition equals
4 the aperture divided by the square of the wavelength, \underline{d}^2/λ .

5 It is also known that beyond this transition, in the far
6 field, the expansion of the beam follows the half-angle θ de-
7 fined by the ratio of wavelength to aperture, roughly $\theta \approx \lambda/\underline{d}$.
8 Traditionally this degradation of the beam is called the beam
9 "divergence".

10 Now in my invention the aperture \underline{d} is typically on the
11 order of $2\frac{1}{2}$ to 5 cm (one or two inches) although it can readi-
12 ly be made considerably larger, and the longest wavelength is
13 preferably about 647 nm. The transition region accordingly
14 lies at least $(2\frac{1}{2} \text{ cm})^2/(647 \text{ nm}) = 965 \text{ m}$, or roughly a kilome-
15 ter, away from the projector.

16 In other words my invention operates entirely within the
17 near field, out to a kilometer (five-eighths of a mile) — and
18 this can be extended straightforwardly to considerably longer
19 distances at the cost of larger optics. Even beyond that dis-
20 tance, beam divergence is less than $\lambda/\underline{d} = (647 \text{ nm})/(2\frac{1}{2} \text{ cm}) =$
21 0.025 mrad , or roughly one part in nearly 40,000 — one
22 millimeter per forty meters.

1 Therefore, in a throw extending beyond the near field by
2 400 m the beam would suffer a divergence of only a centimeter.
3 Assuming an only moderately tall (e. g., 10 m or more) image
4 after such a long throw, and with only one-inch optics, even
5 this divergence is finer than 1/1000 of the image height.
6 Accordingly, with care in selecting constructional details
7 suited to the intended application, the diffraction-imposed
8 limits to sharpness depth should never come into play in the
9 practice of my invention.

10 The preferred form of my invention is slightly complica-
11 ted by the fact that I do not wish to transmit a cylindrical
12 projection beam (i. e. a beam of constant cross-section) to
13 the viewing screen or other medium. Rather I wish to use an
14 expanding or conical/pyramidal beam 45, so that the image on
15 the screen can be much larger than the projector optics.

16 The character of this beam 45 somewhat defies conventio-
17 nal semantics, since it is factually a spreading or diverging
18 beam — and it is of course a laser beam — but this "diver-
19 gence" differs from the conventionally conceived "divergence"
20 of a laser source. In the conventional lexicon, as noted
21 above, that term refers to diffraction-introduced degradation
22 of the beam.

23 Again, that degradation applies to each ray or pencil
24 within a laser beam. It represents not only a spreading of

1 the beam as a whole, and not only a spreading of each individ-
2 ual ray, but also a confusion or crosstalk as between rays.

3 According to my invention the degradation of the beam is
4 minuscule, and through provision of adequate aperture dimen-
5 sions can be made negligible for virtually any desired projec-
6 tion distance — subject to availability of adequate laser
7 power for the corresponding viewing distance and desired image
8 size. For this reason to avoid misunderstanding in describing
9 the projection beam of my invention I have used the term "ex-
10 panding" rather than "diverging".

11 Now it will be understood that my invention is able to
12 display sharp, bright images on projection media at extremely
13 varied distances from the projector. This does not merely
14 mean, as in the case of a conventional motion-picture projec-
15 tor, that my projector can be adjusted to show sharp moving
16 pictures on a screen at any selected distance.

17 Rather it means that the projector of my invention can
18 project sharp pictures on a screen at any distance without
19 adjustment — and furthermore that my projector can project
20 sharp pictures on multiple screens or other objects at differ-
21 ent distances simultaneously, and still without adjustment.
22 Naturally adjustment may be desirable to change image size,
23 but not for sharpness.

1 It remains to discuss how these unique capabilities of my
2 invention can be exploited to provide extraordinary visual ef-
3 fects. Several such embodiments of my invention are disclosed
4 below.

5 (i) structural exteriors — To illustrate on a me-
6 dium scale the extraordinary capabilities of my invention, a
7 projector 101 (Fig. 30) can be positioned to project images
8 onto a group of buildings 147 that are at distinctly different
9 distances from the projector. For instance the buildings may
10 include one structure 147d which has a surface generally at
11 right angles to the center of the projection beam 145, another
12 building 147e that is further away and steeply angled to the
13 beam, so that the beam almost grazes the building, and a third
14 building that is still further away and is a dome.

15 The first-mentioned structure 147d also has a side face
16 that is essentially parallel to the beam, and which the beam
17 only grazes in passing. (In the grid-marked perspective sec-
18 tion of the drawing at far left, the grid lines are intended
19 to show the contours of the structures — not a grid of the
20 projected image.)

21 The projected images may be seen from any of a great num-
22 ber of observer positions 178. If viewed from the position of
23 a person 178a near the projector, all portions of the pro-
24 jected image on the several structural surfaces have substan-

1 tially the sharp, properly illuminated and properly propor-
2 tioned appearance that they would have if the image were
3 simply projected onto a screen at the distance of, say, the
4 nearest building 147a — except of course that any part of the
5 image projected toward the empty space between the two more-
6 remote buildings is not visible.

7 From that observing position 178a, the topmost part of
8 building 147e as shown receives a part of the image projected
9 above the near building 147d. Even that part of the image
10 should look normal, except to the extent that the observer's
11 eyes are below the projector position.

12 If seen from other positions 178b, 178c, all parts of the
13 image appear quite sharp, but with certain exceptions. If the
14 projected image is raster generated, and if a person 178c
15 stands quite near the remote buildings 147e, 147f on which the
16 raster is gigantically enlarged, the person probably is able
17 to visually resolve raster lines so that the image may appear
18 coarse.

19 Analogously in the case of a nonraster image such as a
20 photographic transparency projection (Figs. 19-20), the obser-
21 ver may be able to see grain in the original photograph (or
22 copy) 560. For a live natural image (Fig. 21) the observer
23 178c may be able to perceive the focal limitations of the
24 original pickup lens 701.

1 Where the image is stretched by the cosine effect across
2 the face of the building 147e which is angled to the beam —
3 or over receding portions of the dome 147f — that same obser-
4 ver 178c sees image elements defined sharply, but distorted by
5 the stretching. The ultimate form of this effect is along the
6 grazing side face of the first building 147d, where substan-
7 tially no image at all can be seen. Brightness too is distort-
8 ed by projection distance, and such peculiarities can be seen
9 by such an observer who is close to the projection medium.

10 Intermediate visual effects are perceived by an observer
11 178b in a position that is intermediate between the two posi-
12 tions discussed above. When planning a show of the sort that
13 is schematically laid out in the drawing, the visual designers
14 of course take into account the vantage points from which ob-
15 servers will be permitted to see the performance.

16 The designers select and arrange objects within the image
17 frame so that desired visual effects will appear on the vari-
18 ous structures. For instance the stretched appearance of im-
19 age elements on the angled building 147e or on the dome 147f
20 may be used to dramatic effect — or alternatively may be com-
21 pensated by providing a carefully controlled compression of
22 the image in that area — if it is known that an important
23 fraction of the audience is to see the image from a vantage
24 which gives that stretched effect. If desired, brightness in

1 various image portions can be boosted or suppressed (prefera-
2 bly by manipulating the original image data) to produce natu-
3 ral appearance from such a vantage.

4 As noted above, the example here is at an intermediate
5 scale. Much larger projection configurations are feasible, as
6 for instance projection from far greater distances into the
7 range of kilometers.

8 Depending upon audience position, it may or may not be
9 necessary to project images in very greatly enlarged form;
10 where that is not necessary, typically no special power or
11 brightness constraints are imposed. For example if an image
12 is projected eight hundred meters to a screen, but then the
13 audience is positioned so that the screen as seen by the audi-
14 ence subtends only about the same visual angle as a normal
15 movie screen, the power in the projection beam need be no
16 greater than would ordinarily be used in a normal movie house.

17 In such situations what is particularly extraordinary
18 about the performance of my invention may be primarily only
19 the ability to hold sharpness over a great projection dis-
20 tance. Similarly for projection onto canyon or cliff walls
21 where extremely large images are desired, but where the images
22 are viewed from audience positions near the projector, for in-
23 stance — so that, once again, the image as seen by the audi-
24 ence subtends only a relatively small or ordinary-size visual

1 angle — the power in the projection beam need be only what
2 would be used in a more commonplace projection environment.

3 On the other hand for relatively close viewing of such
4 huge images on cliffs or the like, correspondingly high beam
5 power naturally is necessary. Image color balance can be
6 modified to partly compensate for color of projection media.

7 (ii) structural interiors — The converse of pro-
8 jection onto the outside of a dome is projection onto the in-
9 side 247 (Fig. 31). The visual effects again will differ with
10 positions of observers 278d, 278e relative to the projector
11 201 that generates the image-carrying beam 245.

12 For example, if a rectangular grid is projected onto the
13 ceiling and far wall of the dome, as in the two left-hand sec-
14 tions of the illustration, an observer 278e who is centrally
15 positioned about midway between the projector and the far wall
16 of the dome sees a bottom-enlarged (i. e., distorted) view of
17 the grid — as in the lower-right-hand section of the drawing.
18 This is because the lower far wall of the dome is farther from
19 the projector 201 than is the top of the dome, yielding a
20 greater distance in which the beam can expand.

21 An observer 278d just next to the projector, by compari-
22 son, should see the rectangular grid very nearly as it leaves
23 the projector. The same distance which makes grid units at
24 the bottom far wall actually larger than those at the apex al-

1 so serves to make those larger grid units appear smaller to
2 the observer.

3 In addition the effects in such a viewing space may vary
4 greatly with the degree of beam expansion selected and imple-
5 mented through choice of projection lens 44 (Fig. 1). Those
6 skilled in the art will recognize a great many variations of
7 the embodiments discussed above.

8 (iii) liquid (and like) sheets and sprays — Simi-
9 larly, instead of static solid structures, some objects that
10 are used as projection media may be transitory or fragmented
11 surfaces such as diverse water-fountain sprays 347d, 347e
12 (Fig. 32) or waterfalls 347f. These too may be at greatly
13 differing distances from the projector 301 — but, again by
14 virtue of the infinite-sharpness effect, the images 346 on
15 these water surfaces are sharply delineated (to the extent
16 possible with the diffusion inherent in water sprays etc.).

17 A single projected image may be carefully designed, in
18 anticipation of a specific position for the projector 301 in
19 relation to a particular assemblage of such media, so that for
20 example no image element will be projected toward regions of
21 space where no desired projection medium 347 is expected.
22 Thus in operation the projection beam may contain only image
23 elements 346d, 346e, 346f that are respectively aligned with
24 the flowing water surfaces 347d, 347e, 347f.

1 Naturally such dramatic effects are optional, but can for
2 instance include projecting a moving image of one person — a
3 dancer, for example, or a clown or a soldier respectively —
4 onto each of the differently spaced water sprays 347d, 347e or
5 sheets 347f. Narrative or musical effects can issue from a
6 respective loudspeaker or live performer positioned at each
7 image.

8 In addition to sheets and sprays of water in the form of
9 liquid, equivalently water and other media can be used in
10 other forms such as clouds, fog and ice. In any of these ca-
11 ses, if the surface itself is independently controllable — as
12 for example in the case of computer-controlled fountains and
13 other sprays — additional useful special effects can be ob-
14 tained even if plural surfaces are aligned along a common pro-
15 jection axis.

16 More specifically, the closer fountain can be turned off
17 so that all the light bypasses the position of that fountain
18 and proceeds to the position of another fountain that is far-
19 ther from the projector. Analogously, such effects can be
20 made more subtle or interesting by only feathering or other-
21 wise changing the density or other character of the first
22 spray — rather than turning it completely on or off — to
23 shift the balance, progressively, between projection primarily
24 onto that spray or primarily onto the more-remote spray.

1 (iv) successive scrims — In the case of the water
2 sprays and surfaces discussed above, images may be either di-
3 rected to water elements that are laterally spaced apart, or
4 partially projected through one such element to another behind
5 it. The latter arrangement may also be mimicked in nonliquid
6 elements that are nevertheless translucent or only partially
7 reflective, such as stage scrims 447d, 447e (Fig. 33).

8 Whether made of liquid or of solid mesh, the more-forward
9 partially transmissive surfaces 347d, 347e, 447d, 447e typi-
10 cally can reflect to the audience only filmy or gauzy but
11 nearer images, while the rearwardmost surfaces 347f, 447f may
12 be used to reflect perhaps more solid-seeming but also more
13 distant images. The degree of transparency or translucency of
14 a water surface or scrim can be adjusted by the density of the
15 droplets, mesh or weave, thereby adjusting the balance between
16 brightnesses of the nearer and more distant images.

17 Although filmy in the sense of being projected on a mesh
18 or other noncontinuous surface, all the images 346, 446 are
19 sharp. If the forward scrims 447d, 447e extend across an en-
20 tire stage (e. g. behind a proscenium 479), so that the pro-
21 jection beam 445 can reach the rearward scrims only by passing
22 through the forward ones, opportunities for separation of ima-
23 ges in space are somewhat restricted.

1 Nevertheless many useful stage effects can be created
2 through exploitation of the infinite sharpness of my invention
3 and the consequent sharp-appearing images on successive
4 scrims. Projection of sharply defined abstract art or geomet-
5 ric figures, for example, that materialize on the several
6 scrims in series but with progressively increasing size, may
7 be well adapted to presentations with scientific or futuristic
8 themes.

9 In addition, carefully designed images projected at suit-
10 able angles onto successive scrims — and with the audience
11 positioned in a somewhat restricted angular range — can ap-
12 pear to hover between two scrims in an interesting kind of
13 three-dimensional effect. This phenomenon may be related to
14 Nader-Esfahani's discussion in U. S. Patent 5,556,184.

15 (v) axially spaced natural objects: foliage —
16 Still another class of projection media are living things.
17 Particularly interesting image effects may be obtained by pro-
18 jection on trees 547 (Fig. 34), vines, bushes, and other
19 plants. As shown in the drawing, an image set may be prepared
20 for projection that contains components at roughly left, right
21 and center that are aligned for projection onto respective
22 trees 547d, 547e, 547f.

23 The show may be viewed from near the position of the pro-
24 jector 501, or if preferred from an audience position somewhat

1 off to one side as actually demonstrated by the illustration.
2 Once again different moving images may appear sharply on each
3 of the trees — made, for instance, from dramatic film clips
4 of faces (e. g. statesmen, actors, singers, storytellers), or
5 perhaps of cartoon characters, animals, fish, birds etc.

6 (vi) axially spaced natural objects: living crea-
7 tures — In many of the foregoing exemplary embodiments of my
8 invention I have suggested projecting images of living people
9 onto inanimate objects. Another creative form of my invention
10 encompasses instead projecting images onto living people 647
11 (Fig. 35).

12 For instance images 646 of inanimate (or animate) objects
13 — such as flags, swords, cannons, or even scenery — might be
14 projected onto groups of people. This can be done in such a
15 way as to simultaneously illuminate the people and superimpose
16 upon them images of emblems or icons related to their dramatic
17 roles.

18 One such scheme appears in the illustration. Actually in
19 an outdoor scene, a group of actors 647d costumed as native
20 Americans is standing on a hill, relatively near to the pro-
21 jector 601. In a more-distant grouping and considerably lower
22 are other actors costumed as frontiersmen and mounted on
23 horses.

1 A sharply defined image of a peacepipe (not shown), with
2 smoke curling above it and a fluttering feather below, is pro-
3 jected on the upper group. An image of a ranch house (not
4 shown), or perhaps a small child (not shown) playing with an
5 old-fashioned wooden toy, is projected — from a different
6 part of the same projector, but simultaneously — onto the
7 lower group.

8
9
10 i) Exemplary dimensions — Following are representative
11 approximate dimensions used in my prototype projector.

12
13 milli-

14 meter inch item

15
16 in the red channel:

17 240 9.45 distance A (Fig. 2) from the laser 10r to
18 the galvanometer 21r axis

19 50 1.97 distance B from the negative lens 18r to
20 the galvanometer 21r axis

21 4 0.16 distance C from the cylindrical lens 19r to
22 the galvanometer 21r axis

1 interchannel:

2 240 9.45 offset D between the red and blue channel

3 mirror centerlines

4 120 4.72 offset E between the red and green channel

5 mirror centerlines

6 120 4.72 offset F between the blue and green channel

7 mirror centerlines

8 100 3.94 distance L from the blue-green laser to the

9 dichroic color separator 12gb

10

11 in the green channel:

12 4 0.16 distance G from the cylindrical lens 19g to

13 the galvanometer 21g axis

14 50 1.97 distance H from the negative lens 18g to

15 the galvanometer 21g axis

16 70 2.76 distance J from the folding mirror 16g cen-

17 terline to the galvanometer 21g axis

18 80 3.15 offset distance I along the crosspath 15g,

19 between the dogleg paths 17g, 13g

20 100 3.94 distance M from the dichroic color separa-

21 tor 12gb to the folding mirror 14g

22

in the blue channel:

240	9.45	distance N from the blue-green laser 10bg to the galvanometer 21b axis
60	2.36	distance O from the blue-green laser 10bg to the folding mirror 14b
50	1.97	distance P from the negative lens 18b to the galvanometer 21b axis
4	0.16	distance Q from the cylindrical lens 19b to the galvanometer 21b axis

in the modulator tier:

110	4.33	distance R (Fig. 3) between the forward planes 30r, 30g of the red and green modulators
330	12.99	distance S between the forward plane 30g of the green modulator and the rear apex of the projection lens 44
220	8.66	distance T between the forward plane 30r of the red modulator and the rear apex of the projection lens 44
100	3.94	diameter U of the projection lens 44
120	4.72	offsets V between the centerline of the green modulator 30g and the centerlines of the red and blue modulators 30r, 30b

1	240	9.45	offset W between the centerlines of the red
2			and blue modulators 30r, 30b
3	50	1.97	length X (Fig. 4) of each cube 25r, 25g,
4			25b
5	103	4.06	height Y of the projection lens (output
6			objective) 44
7	70	2.76	width Z of the red-channel folding mirror
8			37r
9	50	1.97	height AA of each beam-splitter/analyzer
10			cube 25r, 25g, 25b
11	320	12.60	vertical distance BB from the horizontal
12			midplane of the upper tier to the top
13			surfaces of the cubes 25
14	20	0.79	height CC of each cylindrical lens 19
15	10-20	0.39	
16		to 0.79	widths DD of cylindrical lenses 19
17	30-50	1.18	
18		to 1.97	focal lengths of cylindrical lenses 19
19	44	1.73	overall width EE (Fig. 4a) of each modula-
20			tor 30
21	34	1.34	overall height FF of each modulator 30
22	70	2.76	diameter of each recollimator lens 23
23	310	12.20	focal length of each recollimator lens 23
24	60	2.36	diameter of each modulator output lens 36

250 9.84 focal length of same

25 0.98 diameter $2r$ (Figs. 25a, 29) of the laser
aperture

~22 0.87 diameter $2m$ across the beam as defined by
the limb L (Fig. 25a).

Although these values have been found to lead to excellent
results, I continue to experiment with component substitutions
in the interest of still further enhancement.

It will be understood that the foregoing disclosure is
intended to be merely exemplary, and not to limit the scope of
the invention — which is to be determined by reference to the
appended claims.